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Composite Panel Impact Testing for the Down-Selection of Material for Use in the Outer Shell of Football Helmets

Natalie Genevieve Patzin
Clemson University

COMPOSITE PANEL IMPACT TESTING FOR THE DOWN-SELECTION OF MATERIAL FOR USE IN THE OUTER SHELL OF FOOTBALL HELMETS

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by
Natalie Genevieve Patzin
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Accepted by:
Dr. John DesJardins, PhD, Co-Committee Chair
Dr. Gregory Batt, PhD, Co-Committee Chair
Dr. Delphine Dean, PhD

ABSTRACT

Each year, there are an estimated 3.8 million sports-related concussions that occur in the United States alone, the majority occurring during football collisions. These staggering numbers occur even with the use of mandated protective helmets, which are designed to decrease potential brain injuries. The outer shell of a football helmet acts as a shield for vulnerable areas of the cranium by providing the initial impact force dispersion to allow a more distributed load to be transferred to the inner foam padding. The current material standard for the exterior casing is a polycarbonate blend. Multiple studies demonstrate insufficiencies in current helmets due to limitations in energy absorption and dissipation.

This study focuses on examining twenty-two different composites configurations for an initial down-selection to determine potential use in the outer shell of the football helmet. Composites were composed of variations of multiple fibers including: Innegra, Kevlar, basalt, E-glass, S-glass, and carbon. Composite materials have proven to be beneficial in a variety of applications due to their decreased weight and exceptional energy absorption and dissipation performance in low velocity impact conditions, which are representative of typical football collisions.

Flat panel composite specimens underwent dynamic drop weight impacts at low velocity impact conditions of 20 J according to ASTM D7136-12. A Cushion Testing system, the Lansmont Corporation TP3 Data Analysis Software, and an Olympus i-Speed3 High Speed Camera were used to capture and analyze the response of the composite during the impact event. The acceleration, duration, and change in impact and

rebound velocities were recorded, analyzed, and compared to the response of polycarbonate under impact conditions.

Several composite configurations demonstrated promising results. These composites were fabricated with lower densities than polycarbonate and experienced a greater change in kinetic energy compared to polycarbonate; illustrating the potential for their use in the outer shell of football helmets for improved energy absorption. Based upon the results, the top ten composite performers during impact testing have been chosen to advance on to Phase II testing to evaluate the response of these materials under greater impact energies.

DEDICATION

To my family, for their never ending love, support, and motivation.

ACKNOWLEDGEMENTS

There are numerous people who deserve recognition for their dedication and support throughout this project. I would first like to thank my advisor, Dr. John DesJardins. He has provided a wealth of knowledge and advice to help guide me throughout my research endeavors. His dedications to his laboratory work and graduate students' success is second to none. I would also like to thank my other advisor, Dr. Gregory Batt, for his support throughout the completion of my project. Both Dr. DesJardins and Dr. Batt have been exceptional mentors to me throughout my entire graduate career. I would also like to thank my last committee member, Dr. Delphine Dean for her support and guidance throughout this project. A special thank you to the Clemson University Bioengineering Department. The professors in the department have helped me to channel my passion of helping others and provide me with a wealth of knowledge to help me succeed in my future endeavors. I would especially like to thank my Undergraduate Research Assistants, Nathan Walters, Jennifer Anderson, and Drew Barry for their endless assistance and friendship throughout this project. All have gone above and beyond what was ever asked of them, and I am forever grateful for all of their help. Without their help, this project would not have been the same. I would also like to thank the members of the Laboratory of Orthopaedic Research and Design. The guidance provided by all members of lab have helped me to succeed. I would also like to thank our industry collaborators, Innegra Technologies and B&W Fiberglass. Additional recognition is due to Elizabeth Cates of Innegra Technologies for sharing her wealth of knowledge on composite materials. Finally, I would like to thank my family and friends for their endless support and motivation each and every day.

Thank you!

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CHAPTER ONE

GENERAL INTRODUCTION

Football is one of America's favorite past times. Fans thrive to see the big hits between players, but it is these collisions between the athletes that lead to head impact injury. With growing media attention and publicity to concussions and the potential dangers of the sport in relation to head impact injuries, there is a tremendous need to understand head impact collisions to help decrease the prevalence of head impact injuries related to football. This thesis describes the development of testing methods and preliminary results of dynamic drop weight impact testing of flat panel composite specimens for the use in the outer shell of football helmets. This work begins with a literature review of the development, evolution, and components of American football helmets, the clinical injuries associated with head impact collisions in football, the biomechanics of the struck player related to head impacts, and an overview of material properties and dynamic drop weight impact testing on composite materials. It then discusses the materials and testing methods used, as well as the results, discussion, and conclusions from the data of the study.

1.1. Project Goals and Aims of the Study

The overall goal of this work is to design and test twenty-two different composite specimen configurations for the use in the outer shell of the American football helmet.

Currently, the outer shell of the football helmet is made of a polycarbonate/polyethylene terephthalate blend [20]. Due to the growing media attention related to head injuries, the performance of current materials of the football helmet have been put under great scrutiny. There is a significant clinical need to understand concussions and traumatic brain injury (TBI) associated with football head impacts. Current research on football helmet testing has mainly been focusing on how to improve the design the inner foam padding of the football helmet to better absorb and dissipate more energy to ensure less energy is transferred to the players head upon impact. However, the work described in this thesis has shifted its focus from the padding of the football helmet to the outer shell of the football helmet. Our focus is to use a material that is better able to absorb energy so that less energy is transferred from the outer shell to the inner padding to the football players head. Composites are known for having good energy absorption and dissipation properties by distributing the impact load laterally within the material. The work presented in this thesis seeks to aid in understanding which configuration of a variety of composite specimens perform the best under dynamic drop weight impact testing by providing the best energy absorption properties for potential use in the outer shell of the football helmet.

As part of this thesis, a literature review was conducted, followed by the development of testing methods and preliminary testing towards accomplishing three experimental aims. The first aim was to fabricate a composite panel that has a density equal to or less than the standard polycarbonate sample. This was accomplished by Innegra Technologies and B&W Fiberglass in collaboration with Russ Emanis, the fabricator of the composite panels. The second aim was to perform a series of dynamic drop weight impact tests in order to down-select ten composite configurations to continue further in the testing. Dynamic drop weight impact testing assessed the changes in specific variables such as acceleration, duration, impact and rebound velocity, and displacement of the material. The third aim was to down-select composite specimens based on samples that performed with a greater change in kinetic energy measurement than the standard polycarbonate sample and to obtain a displacement measurement that is equal to or less the standard polycarbonate material. The third aim was accomplished by performing dynamic drop weight impact testing on flat panel composite specimens. Laboratory software and high speed video were used to capture the variables of interest in the dynamic drop weight impact testing.

The work presented in this thesis was developed and conducted over a 12 month period, and focuses on a comprehensive literature review used to aid in the development of testing methods, followed by the presentation of results of dynamic drop weight impact testing from the analysis of twenty-two different flat panel composite configurations responses.

1.2. Clinical Significance

The three experimental aims were developed in collaboration with Innegra Technologies (Greenville, SC) and B&W Fiberglass (Shelby, NC). Both Innegra Technologies and B&W Fiberglass are materials based companies whose fibers are used within products in the sports market. Due to the growing need for a better material within the football helmet to help reduce the prevalence of concussions in the contact sport, Innegra Technologies and B&W Fiberglass have partnered to combine both of their proprietary materials to develop a better absorbing external shell material for the football helmet.

In the United States alone, there are 1.5 million traumatic brain injuries each year. Seventy-five percent of these cases are mild traumatic brain injuries (mTBI) such as concussions, and 300,000 of these cases are due to sports related injuries [2]. American football is known for having the highest occurrence of mild traumatic brain injury (MTBI) of any sport in the United States, and the occurrence has been increasing each year. Nearly 20% of football players experience a MTBI during a regular football season [2, 4]. With over 4.2 million football athletes in the United States alone, there is a tremendous need to develop a better energy absorbing and dissipating outer shell to help reduce the peak linear and rotational accelerations experienced by the struck player to aid in decreasing the prevalence of concussions [4, 21].

In addition to the experimental work, this thesis provides a comprehensive literature review of football helmets and football helmet research in relation to head impact injuries sustained in American football.

CHAPTER TWO

EVOLUTION OF AMERICAN FOOTBALL HELMETS

The primary function of the football helmet is to decrease the potential for brain injury by increasing the duration of impact. Increasing the impact duration allows for the brain to experience a lower mechanical load within the skull, as well as a lower acceleration to the head. Increasing the duration of impact is accomplished through deformation of the football helmet materials [22, 23].

2.1. Evolution of the Football Helmet

The first voluntary use of the football helmet happened during an Army-Navy game in 1893. However, the use of helmets in American football did not become mandatory until 1939 for the National Collegiate Athletic Association (NCAA) and 1940 for the National Football League (NFL) [8]. Football helmets have changed drastically since they first debuted. When football helmets were first introduced to the sport, they were made of a leather material [8, 9]. Since then, changes have occurred to the football helmet. These changes to the design and materials include: the transition from a leather helmet to a plastic polycarbonate (PC) shell, the addition of a facemask in 1951, and the introduction of energy absorbing padding [8, 9].

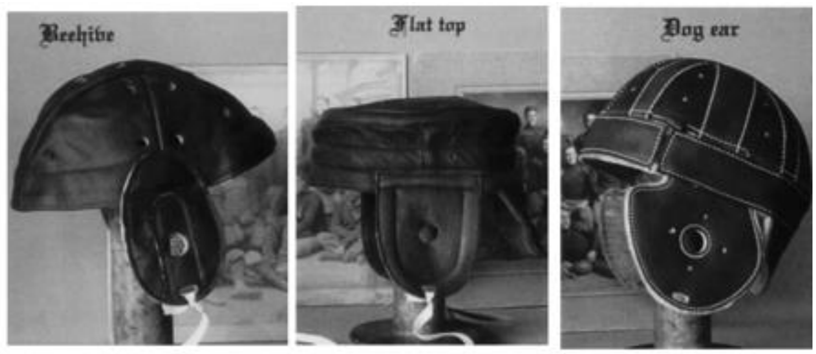


Figure 2.1 Display of old leather football helmets (L: “behive”; M: “flat-top”, R: “dog-ear”) [8].

It was during the 1970s when changes started occurring with the design of football helmets. Thicker internal padding was added, and the outer shell was smoothed out to a plastic material. These changes helped increase the pulse duration of impact and therefore decrease the mechanical load experienced by the brain [1].

Figure 2.2 Collection of American football helmets from 1970-2010 showing the evolution of changes in design [9].

In a study performed by Viano et al., researchers set out to investigate the morphologic evolution of football helmets with the goal of evaluating the changes in size and weight of helmets from pre-1970s to 2010. Figures 2.3 and 2.4 below shows the changes in the helmet weight as well as the helmet dimensions throughout the years. It can be seen that both the weight and dimensions of football helmets have increased slightly over the years. Currently, helmets range in weight from 1.93 to 2.05 kg, which is nearly three times the weight of the 1970 helmets, and the dimensions of the helmet are currently 32.4 ± 0.5 cm long, 28.1 ± 0.3 cm tall, and 24.2 ± 0.2 cm wide [9].

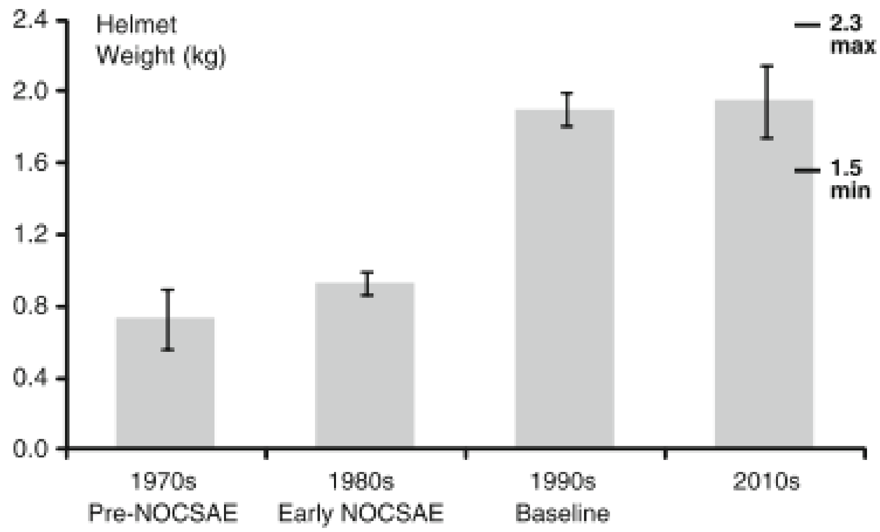


Figure 2.3 Representation of the changes in the weight of helmets pre-1970s to 2010 [9].

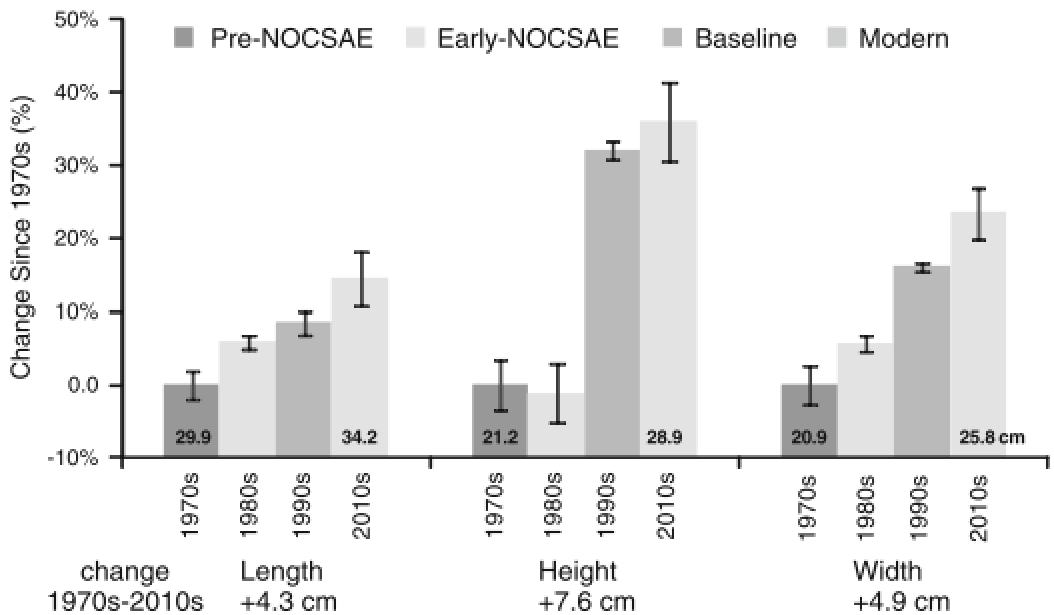


Figure 2.4 Representation of the changes in dimensions (length, height, and width) of helmets pre-1970s to 2010 [9].

A recent follow-up study performed by Viano et al., sought to evaluate the impact performance of modern football helmets by comparing the translational acceleration, rotational acceleration, and HIC of 17 currently used football helmets to 3 baseline 1990s helmet performance (Riddell's old style VSR4 and Schutt's Pro Air II). For this study, parameters were chosen to compliment the National Operating Committee on Standards for Athletic Equipment (NOCSAE) Helmet Certification Standards as well as information from a recent NFL study on impacts causing concussions. Eight impact sites were tested at four speeds (5.5, 7.4, 9.3, 11.2 m/s) and two different temperatures (22.2 and 37.8 °C) [10].

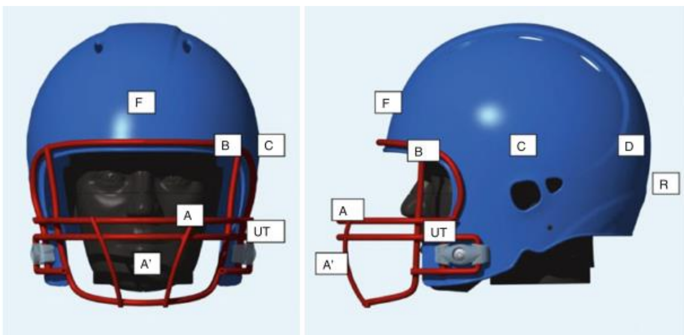


Figure 2.5 Location for the eight impact sites used in the Viano et al. study chosen based upon NOCSAE Standards and NFL video analysis of severe impacts (F, C, D, and R: helmet shell; A, A', B, and UT: facemask) [10].

From the follow-up study by Viano et al., it was found that four of the newer modern football helmets performed better than the 1990 baseline helmets. These helmets were the Schutt DNA PRO, the Riddell Revolution, Riddell Revolution IQ, and Riddell Revolution Speed. These four helmets performed better by better dissipating impact force and absorbing energy within the padding. The average weight of these helmets were 2.00

kg which is a 6.8% increase from the 1990 baseline helmets. Also, the length and width of the newer modern helmets increased by 7.5% and 5.4% respectively. These subtle changes in weight, length, and width prove that football helmets can have significantly greater and safer protection by slightly modifying the dimensions [23].

Overall, from this study, it was proven that newer football helmets have increased in both size and weight. Although not all helmets showed statistically significant changes in performance, most (11/17) of the newer helmets tested offered better protection from the 1990s baseline helmets [10]. It is important to consider the effects of increasing the mass and density of the materials used in the football helmet. Increasing the weight and density of the materials must be done within reason because doing so increases the weight and mass that could interact with the player's neck structure making the player more susceptible to fatigue, injury, and/or concussions [23].

2.2. The National Operating Committee on Standards for Athletic Equipment

The National Operating Committee on Standards for Athletic Equipment (NOCSAE) originated in 1969 with the primary goal to improve the safety of athletes by beginning research aimed at head protection. The objective was to establish a standard that tested a football helmet's ability maintain effectiveness after numerous impacts under a variety of conditions [8, 24]. Standards for assessing the impact performance of football helmets were first established by NOCSAE in 1973. These standards were developed resulting from studies performed by Wayne State University (WSU)

Department of Neurosurgery. In 1971, NOCSAE sought the help of WSU to aid in the development of voluntary standards for the impact performance of helmets. These initial tests used Z-90 metal headforms and cadavers equipped with football helmets to assess the performance of the helmets. Through these initial tests, a newer head model was created that was made of a synthetic material. This model headform was more representative of the human head. From this new representative headform and baseline helmet testing, initial voluntary standards were established. These standards helped to greatly reduce the SI and HIC associated with football helmet impacts [3, 12].

In 1978, it became mandatory for all helmets used in college football to be approved by NOCSAE. Following shortly after, in 1980, it was mandated that all helmets worn by high school players be approved by NOCSAE. By mandating that helmets worn by college and high school players be certified by NOCSAE, the measured SI score values in certified helmets were reduced by half of the original SI score values of helmets previously not certified by NOCSAE [3].

With the adaption of NOCSAE Standards by helmet manufacturers, by 1980, there was a 51% decrease in fatal head injury, a 35% decrease in the prevalence of concussions, and a 65% decrease in cranial fractures observed in youth football. According to a study on helmets certified by NOCSAE compared to those that are not certified performed by Hodgson and Thomas, those helmets not certified by NOCSAE resulted in a SI of 1450, whereas those helmets certified by NOCSAE resulted in an SI of 1064. This means that there was a 55% decrease in the risk of head injury with the development of NOCSAE Standards [3, 12].

Due to the positive results of developing and adapting the NOCSAE football helmet standards, the standards are still being used today. Currently, all helmets used in youth, collegiate, and professional football must be certified by NOCSAE Standards. Since the development of NOCSAE football helmet standards, there has been a 74% reduction in football injury fatalities and a reduction in serious head injuries from 4.25 per 100,000 players to 0.68 per 100,000 players [24]. However, one issue that needs to be addressed is that NOCSAE Football Helmet Standards do not address the issue of decreasing the risk of concussions, it only evaluates the probability of decreasing the risk of head injuries by looking at the Severity Index [3, 12].

2.3. NOCSAE Football Helmet Standard Specifications

The NOCSAE Standard was developed to establish basic performance requirements to conduct standard drop tests on football helmets. The standard provides the impact velocities, performance requirements, and pass/fail criteria for helmet testing. During testing, drop tests must be performed at four different impact velocities (3.46, 4.23, 4.88, and 5.46 m/s) at seven different impact locations (front, side, front boss, rear boss, rear, top, and random). All impacts are performed at ambient (72 °F) and high temperatures (115 °F). Football helmets must be placed on a certified headform that is representative of the human head, and is instrumented with accelerometers [25].

Table 2.1 Location and impact velocities test requirements for NOCSAE Certification [25].

LOCATION - DROP velocities – ft/s (m/s)
(All drop velocities must be within +3% -0%)

	FRONT	SIDE	F. BOSS	R. BOSS	REAR	TOP	RANDOM
Ambient Temperature	11.34 (3.46)	11.34 (3.46)	11.34 (3.46)	11.34 (3.46)	11.34 (3.46)	11.34 (3.46)	11.34 (3.46)
	13.89 (4.23)	13.89 (4.23)					
	16.04 (4.88)	16.04 (4.88)					
	17.94 (5.46)	17.94 (5.46)	17.94 (5.46)	17.94 (5.46)	17.94 (5.46)	17.94 (5.46)	17.94 (5.46)
	17.94 (5.46)	17.94 (5.46)	17.94 (5.46)	17.94 (5.46)	17.94 (5.46)	17.94 (5.46)	17.94 (5.46)
High Temperature		17.94 (5.46)					
		17.94 (5.46)					

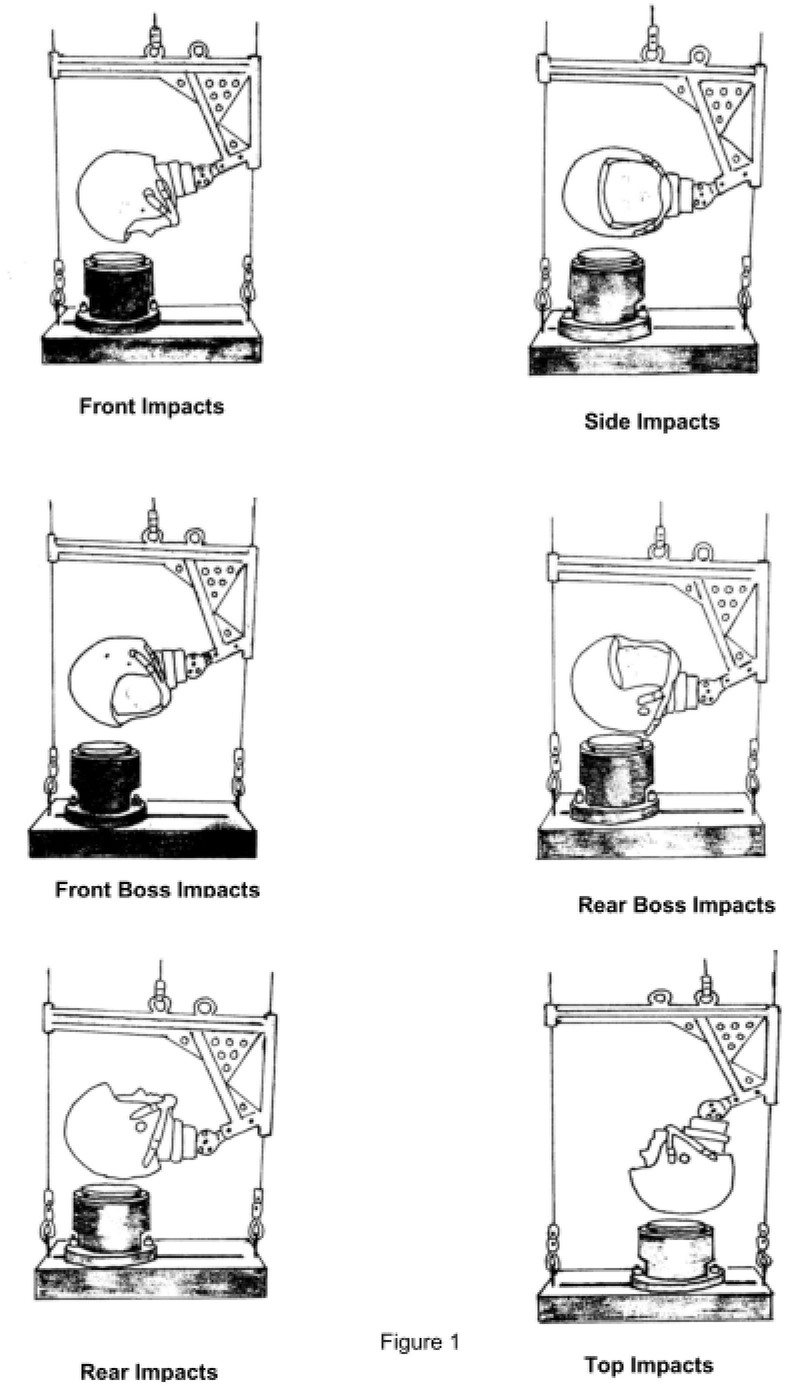


Figure 2.6 Helmet location impacts for NOCSAE Certification [25].

Typical testing involves instrumenting the headform with the helmet and ensuring that the helmet fits appropriately according to the helmet manufacturer's specifications. The headform with the equipped helmet is then dropped in free fall from the appropriate height to ensure that the desired impact velocity is achieved. Upon impact, the triaxial accelerometers measure the resultant acceleration. This data is used to calculate the Severity Index (SI) (see *3.6. Evaluation of Head Injuries: SI and HIC* for mathematical model to calculate SI value) [25].

Based upon the data acquired by the triaxial accelerometers, to pass the NOCSAE standard, no head impact is allowed to exceed an SI value of 1200. Another specific requirement is that the 11.34 m/s impact must not exceed an SI value of 300. A helmet that is certified by NOCSAE must also be able to maintain protective effectiveness during all drop tests as well as be within the appropriate SI boundaries [25].

2.4. Components of the Football Helmet

Riddell, Schutt, Rawlings, and Xenith are the leading helmet manufactures currently producing football helmets on the market [10, 20]. For the 2008-2009 NFL season, 81% of all players wore a Riddell Helmet with the majority of these Riddell helmets being the Riddell VSR4 helmet. This model has been around since the 1990s. Astonishingly, only 25% percent of all NFL players wear some type of newer modern helmet such as the Riddell Revolution or Schutt DNA [10].

There are three layers to the shell of the American football helmet: the outer shell, the inner foam, and the internal padding (see Figure 2.7). The outer layer of the helmet casing is the polycarbonate shell [20]. This exterior casing was designed to shield the delicate areas of the cranium and to dissipate the impact force throughout the outer shell material through deformation of the shell. Nearly 34% of the energy upon impact is attenuated due to deformation of the shell. This is done to ensure that there is not a single concentrated load to the head of the athlete [5, 8, 26]. Typically, the external shell ranges in thickness from 3-5 mm depending on the location [27]. Varying the thickness of the outer shell gives different energy absorption and dissipation properties. However, the challenge becomes making the external shell and internal foam padding thick enough to absorb significant amounts of energy without jeopardizing the size, fit, and performance of the helmet.

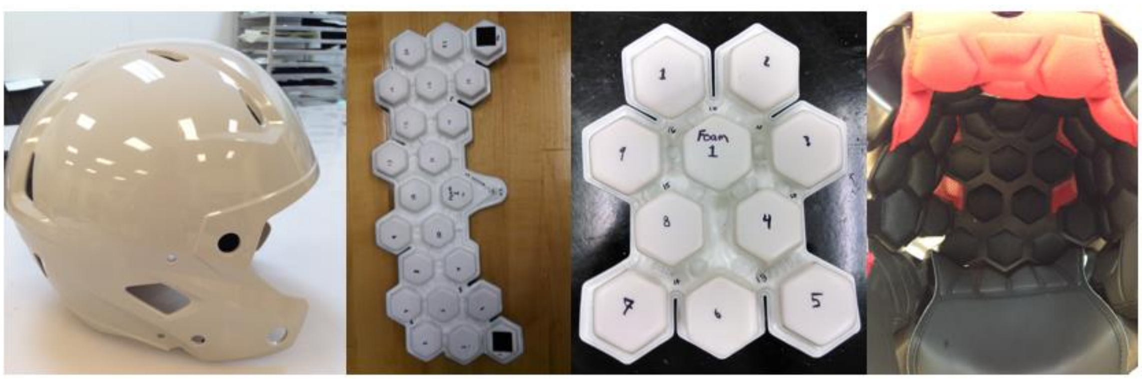


Figure 2.7 Layers of the casing of the football helmet (left: outer shell, left middle/right middle: inner foam, right: internal padding).

The next layer of the football helmet is the inner foam liner usually made of a polymeric foam material. The liner can be made from a variety of materials including vinyl nitrile (VN) foams, expanded polypropylene (EPP) foams, and thermoplastic polyurethane (TPU). The purpose of the inner foam liner is energy absorption and uniform energy dissipation. This is done through deformation of the foam upon impact. [5, 8, 26]. The most internal layer of the football helmet that is in contact with the football player's head, is the internal padding. The function of the internal padding is intended for comfort, improved fit to the player's head, and a washable interface [5, 8, 27].

It must be noted that currently, football helmets greatly reduce the linear acceleration experienced upon impact; however, helmets do not do a good job in reducing the rotational acceleration upon impact [26].

2.5. Changes in Helmet Design Since 1994

Since the formation of the NFL Committee on Mild Traumatic Brain Injury in 1994, there has been a significant increase in the understanding of the biomechanics of concussive impacts. The studies and data released by the committee have been beneficial to helmet manufacturers. This new information has allowed helmet manufacturers to improve the design of football helmets with the aim to reduce the risk of mTBI. Examples of helmets that have been modified and released based upon the information from the committee's studies include the Adams USA Pro Elite, Riddell Revolution, and

Schutt Sport Air Varsity Commander. The newly designed helmets specifically focused on increasing the thickness of the padding on the side (near the ears) and back of the helmets to allow for more energy absorption [12].

The NFL Committee on mTBI reconstructed 10 NFL concussion game impact cases using these newly designed football helmets to evaluate the effectiveness of the changes. The performance of the newly designed helmets was compared to the performance of the previous VSR-4 football helmets in concussive impacts. From these reconstructions, it was found that the newly designed helmets reduced the risk of concussion anywhere from 10-20% [12].

2.6. Current Football Helmet Research

Football impacts and there relation to concussions is a topic receiving a lot of publicity recently. With growing publicity, this puts the pressure on gaining a better understanding of football head impacts associated with head injury risk. See section *3.4. mTBI Committee in the National Football League* for complete research being performed by the NFL as a result of the growing prevalence and severity of concussions.

Research being conducted by universities is also underway. Virginia Tech (VT) is one of the leaders in the field with football helmet research and testing. Currently, many studies are ongoing at VT. Virginia Tech's research is highlighted in Chapter 4.

2.7. Methods to Measure Head Impact

The Head Impact Telemetry (HIT) System (Simbex, Lebanon, NH) is a wireless device capable of detecting real-time measurements of linear and rotational accelerations and impact location experienced by an impacted football players. The device is equipped with six spring-mounted accelerometers. Using a spring-mounted system ensures that the accelerometers are in constant contact with the head. This allows accelerations experienced by the head to be measured and not accelerations experienced by the helmet. Once the system is triggered, it is capable of collecting data for 40 ms after impact. Data that is captured by the HIT System is sent to the Sideline Response System for athletic trainers and medical personnel to monitor. The Sideline Response System is able to observe 64 players at a time [2, 4, 28].

Figure 2.8 Head Impact Telemetry System [2].

Figure 2.9 Head Impact Telemetry System fitted in a collegiate football helmet [2].

CHAPTER THREE

CLINICAL INJURIES ASSOCIATED WITH FOOTBALL HEAD IMPACTS

3.1. Mild Traumatic Brain Injury

A mild traumatic brain injury (mTBI), also known as a concussion, is defined by the Centers for Disease Control and Prevention as a "condition of temporarily altered mental status as a result of head trauma" and relates to brain function [29, 30]. More specifically, Pellman et al. define a mTBI as "any traumatically induced alteration in neural function, which may or may not involve loss of consciousness" [15, 31]. The NFL Committee on Mild Traumatic Brain Injury developed a more broad definition in 1996 defined as "a traumatically induced alteration in brain function, manifested by 1) alteration of awareness or consciousness, including but not limited to being dinged, dazed, stunned, woozy, foggy, or amnesic or, less commonly, being rendered unconscious or experiencing seizures, and 2) signs and symptoms commonly associated with post-concussion syndrome, including persistent headaches, vertigo, light-headedness, loss of balance, unsteadiness, syncope, nearsyncope, cognitive dysfunction, memory disturbances, hearing loss, tinnitus, blurred vision, diplopia, visual loss, personality changes, drowsiness, lethargy, fatigue, and inability to perform usual daily activities" [15].

There are three separate levels of concussions. Each level is defined differently and should be treated with extreme caution. A Grade 1 concussion is defined as “transient confusion, no loss of consciousness, and duration of mental status abnormalities of less than 15 minutes.” Grade 2 concussions are defined as having symptoms incorporating “transient confusion, no loss of consciousness, and duration of mental status abnormalities of greater than 15 minutes.” The most severe level of concussions are Grade 3 concussions, and they are defined by a loss of consciousness for any range of time ranging from seconds to minutes [29].

There exists a great concern about the severity of repeated mTBIs in athletes. There is always the risk of a player becoming severely injured when returning to play before an athlete who sustained a concussion has fully recovered. Returning to play too soon could lead to Second Impact Syndrome which can lead to death. Now that public awareness regarding the severity of concussions has increased, SIS is less common. However, there is the concern regarding the effects of repeated mTBIs on the brain health of athletes. The risk of a player sustaining a mTBI greatly increases for those athletes that have previously had mTBIs. Studies have shown that if a player experiences greater than four concussions throughout his/her career, they are more likely to experience personality changes and fatigue. Also, there is concern with permanent brain damage and worsening of cognitive function due to numerous head injuries [20, 24].

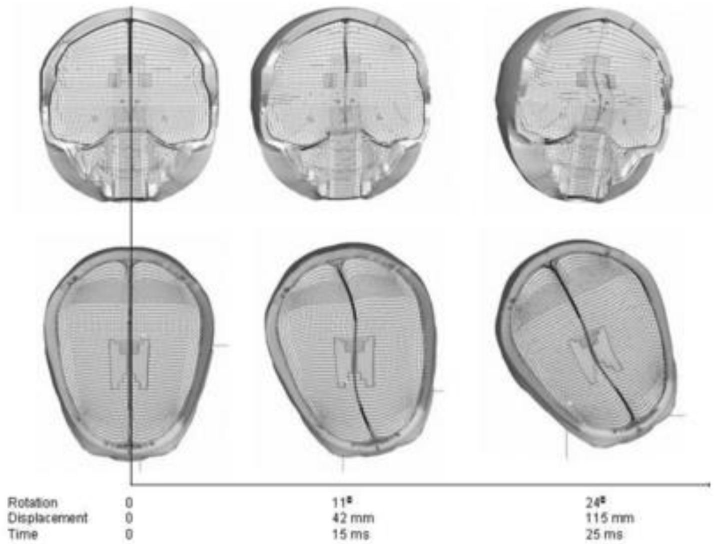


Figure 3.1 Finite element image of the head response and brain deformation at 0, 15, and 25 msec following a NFL concussive impact (top row: frontal view; bottom row: superior view) [12].

3.2. Prevalence of mTBI

The prevalence and understanding of mTBIs are a serious public health concern in the United States. There are a total of 10 million TBIs occurring each year in the world with falls and motor vehicle accidents as the leading cause; 1.4 million of these cases occur in the United States, and 50,000 result in death. These numbers do not include the people who do sustain a TBI but do not seek medical attention [13]. In the United States alone, TBI is the leading cause of disability, morbidity, and mortality among individuals under the age of 45 and leads to a substantial amount of sudden traumatic deaths annually [30, 32]. TBI is the leading cause for nearly half of the traumatic deaths that occur each year; this totals out to 20-30 cases per 100,000 persons [30]. Each year, there 200 cases per 100,000 persons subjected to TBI, and more specifically there are 160-375 cases per

100,000 persons subject to mTBI [15, 30]. The cost that the health care system spends each year on concussions is $56.3 billion dollars [30, 32].

Figure 3.2 Schematic showing the responses to TBI related injuries in the United States each year [13].

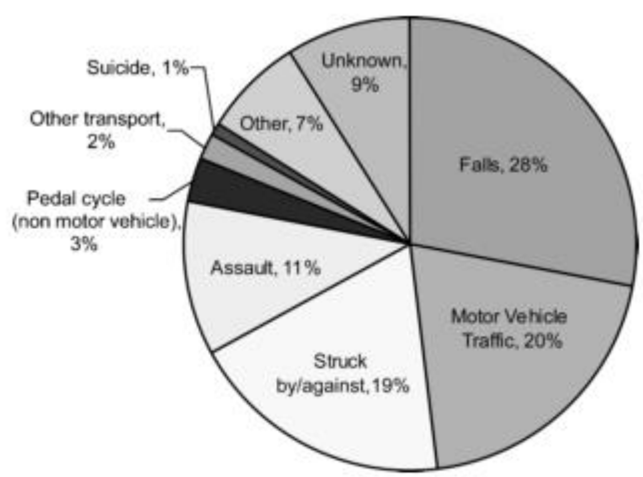


Figure 3.3 Representation of the causes of TBI related injuries within the United States [13].

In 1997, the Center for Disease Control and Prevention estimated that there were 300,000 sports related traumatic brain injuries occurring annually [15, 29]. Recent studies have shown that in terms of concussions, there are nearly 3.8 million sports-related concussions each year in the United States alone with football as the sport with the greatest occurrence [13, 33, 34]. Throughout the 1996-2001 seasons, there were 787 reported concussions in the NFL occurring during preseason, regular season, and postgame play. There were an additional 100 reported concussions that occurred during practice in the NFL from 1996-2001. From the 787 cases of reported concussions, 9.8% (58 cases) of players lost consciousness. The data over six seasons averages out to 0.41 concussions per game in the NFL [15]. Most recently, during the 2013-2014 NFL season, there were 152 reported concussions over a five month period [14].

Figure 3.4 Prevalence of concussions in the NFL for the 2012/2013 (left) and 2013/2014 (right) season based on player position [14].

The prevalence of concussions within the past couple of years has greatly increased. There are numerous reasons for this. One major reason for the increased frequency of the occurrence of concussions includes the broadening of the definition of a mTBI. This change in definition now specifies that a loss of consciousness no longer needs to be sustained in order to experience a mTBI. Nearly 90% of concussion cases sustained during an athletic impact event do not result in a loss of consciousness [35]. The second reason is due to the increased education and knowledge provided by the NFL and researchers from recent studies on the severity of concussions. Players, coaches, and medical staff all have received more training and education related to the effects of concussions, and all are taking more precautions in diagnosing and treating this problem. The third reason is because of the growing publicity regarding the significance of concussions [15, 36]. With increased awareness on the severity of head injuries, there are more players who are willing to report these injuries to medical personnel. A fourth reason includes the extreme cautiousness and conservative treatment by medical staff. The role of physicians and trainers is to protect the player from head injuries and future complications resulting from head injuries. Another reason is due to the increase in strength of the physical athlete. Better weight training and strength and conditioning programs have been developed to make the athlete stronger and faster [24]. A final reason that concussions are more prevalent is due to the changes in the administration of neuropsychological testing. Until recently, this testing was all administered on paper. However, due to recent advancements with technology, this testing is all computerized now making the process much simpler and faster, and in 2007, this testing became mandatory for all NFL teams. These programs aid in the rapid diagnoses of concussions [36].

3.3. Signs and Symptoms of mTBI

There are numerous signs and symptoms associated with mTBI. Often these symptoms overlap with other head injuries making concussions difficult to diagnose. The symptoms of concussions can be categorized into six different groups: general symptoms, cranial nerve symptoms, memory problems, cognitive problems, somatic complaints, and loss of consciousness [12, 15, 36]. Figure 3.5 shows common signs and symptoms associated with each category related to concussions.

General symptoms
- *Headaches*
- *Neck pain*
- *Nausea*
- *Syncope*
- *Vomiting*
- *Back pain*
- *Seizures*

Cranial nerve symptoms
- *Dizziness*
- *Blurred vision*
- *Vertigo*
- *Photophobia*
- *Tinnitus*
- *Diplopia*
- *Nystagmus*
- *Pupil response*
- *Pupil size*
- *Hearing loss*

Memory problems
- *RGA delayed*
- *Information-processing problems*
- *Attention problems*
- *AGA delayed*

Cognitive problems
- *Immediate recall*
- *Not oriented with respect to time*
- *Not oriented with respect to place*
- *Not oriented with respect to persons*

Somatic complaints
- *Fatigue*
- *Anxiety*
- *Personality changes*
- *Irritability*
- *Sleep disturbances*
- *Loss of appetite*
- *Depression*
- *Loss of libido*

Loss of consciousness

[a] RGA, retrograde amnesia; AGA, anterograde amnesia.

Figure 3.5 Signs and symptoms associated with concussions [15].

The NFL analyzed concussion data from 787 concussions throughout the 1996 to 2001 season. From these concussions, headaches (55.0%), dizziness (41.8%), and blurred vision (16.3%) were the most common symptoms associated with concussions from NFL head impacts. When performing physical examinations on concussed players, team physicians and trainers found that the most common signs of a concussion prevalent during a physical exam were difficulty with immediate recall (25.5%), retrograde amnesia (18%), and difficulty processing information (17.5%).

TBI and mTBI are serious injuries that must be treated appropriately. These injuries can lead to long-term disabilities related to physical complications, cognitive and behavioral problems, and emotional distresses. Langlois et al. characterizes TBI as one of the most disabling injuries. Nearly 5.3 million Americans (2% of population) are suffering from long-term complications and disabilities resulting from TBI. Other health issues such as drinking problems, depression, and risk of Alzheimer’s disease have increased risk due to TBI [13].

3.4. mTBI Committee in the National Football League

In 1992, Al Toon became the first NFL player to retire due to post-concussion syndrome. Toon, a stand-out player since 1985 for the New York Jets, was known as one of the best wide receivers in the NFL at the time. Throughout his career he experienced minor headaches and dizziness that went unnoticed by athletic trainers and medical personnel. These problems eventually escalated later in his career and forced him to retire prematurely from his professional playing career [12, 37]. One year later, Merrill Hoge of the Chicago Bears retired due to related complications. These abrupt decisions and actions by NFL players raised questions related to the problems associated with the diagnosis and treatment of concussions [12].

In fear of the direction that the concussion epidemic was headed and to better understand this medical issue, NFL Commissioner Paul Tagliabue accepted and supported the formation of the NFL Committee on Mild Traumatic Brain Injury in 1994 with Dr. Elliott Pellman appointed as chair. This committee was specifically designed to thoroughly address the scientific issues involving the questions and vagueness behind mild traumatic brain injuries. The mission of the committee was to gather and investigate data related to head impact injuries for the protection of all athletes at all competition levels in hopes to increase general awareness of head injuries and to provide information that will help improve the safety in all contact sports [3, 12, 15, 37]. The committee was made up of a wide variety of personnel including team physicians, athletic trainers, and equipment managers, a neurologist, a neurosurgeon, a neuropsychologist, a biomechanical engineer, and an epidemiologist [15, 37].

When the committee was first formed, its primary task was to construct an accepted definition of what a concussion is that will be used consistently by all medical personnel involved with the NFL teams. After several months of deliberation, the committee settled on a broad definition of a concussion in hopes to over identify injuries for preventative safety reasons (definition can be found in section *3.1. Mild Traumatic Brain Injury*) [37].

Once a broad definition of a concussion was established by the committee, the group set out to investigate and better understand the biomechanics behind impacts that caused concussions in professional football. This task was to be accomplished by participating in a project aimed at monitoring the occurrence of concussions within the NFL and analyzing data related to these concussive impacts. These studies including reconstructing NFL impacts, as well as funding research to aid in the understanding of the causes of mTBI [12, 15].

3.5. Other Injuries Associated with Head Impact in Football

Postconcussion syndrome (PCS) is an ongoing disorder that may occur several months to years after receiving a head impact injury, and it is very difficult to treat. Symptoms related to this disorder include the same symptoms associated with concussions including headaches, memory problems, and dizziness. Around 35-50% of people who experience a mTBI report symptoms of PCS anywhere from one to three years following the incident [38, 39].

Based upon data analysis from NFL players who experienced a concussion and did not return to play within seven days, these players were more likely to have experienced loss of consciousness and/or been hospitalized due to their head impact injury. Also, postconcussion syndrome is associated with a greater amount of signs and symptoms of concussion with increased severity such as problems with memory and retrograde amnesia [12].

There is significant speculation between when the concussion symptoms end and the onset of postconcussion syndrome begins. Minimal data exists to analyze the progression of head injury related to postconcussion syndrome. Typically, symptoms of postconcussion syndrome begin one week following the head impact [12].

Second Impact Syndrome was first recognized in 1984. This clinical disease involves acute brain swelling as a result of receiving a second concussion prior to a full recovery from a previous concussion. The swelling of the brain occurs primarily due to complications related to auto regulation of the cerebral circulation which leads to build-up of fluids and an increase in intracranial pressure. SIS usually results in death [29]. There are no reported cases of SIS in the NFL which could be due to the conservative return-to-play procedures [12].

Chronic Traumatic Encephalopathy (CTE) is a severe problem involved with the NFL due to recent suicides of past NFL players who suffered from symptoms of depression related to CTE. Saulle et al. define CTE as a “progressive neurodegenerative disease caused by repetitive head trauma” [40]. Its symptoms include memory difficulty, behavioral and personality alterations, Parkinsonism, and speech and gait abnormalities. On a microscopic level, with CTE there is deterioration of the cerebral hemispheres, medial temporal lobe, thalamus, mammillary bodies, and the brainstem. This injury has been reported with numerous athletes in contact sports such as boxing, football, and wrestling. The exact prevalence of CTE is unknown; however, 17% of people who are subject to repetitive head injuries will develop CTE [41].

3.6. Evaluation of Head Injuries: SI and HIC

Conventional procedures used to assess a head injury risk from a typical football impact are the severity index (SI) or head injury criterion (HIC) which has been adapted and modeled off the Wayne State Tolerance Curve (WSTC) [1, 3, 42]. Current NOCSAE testing standards that are used in the certification of helmets uses the Severity Index (SI) to evaluate the effectiveness of football helmets in relation to head impact tolerance. The SI is a measure of the severity of the impact as a result of the instantaneous acceleration associated with a head impact. SI is calculated using the resultant head acceleration of the football player [1, 25].

For NOCSAE purposes, the SI is calculated using the equation:

$$\mathrm{SI} = \int^{T} a(t)^{2.5} dt$$

Where a(t) is the resultant translational acceleration at the head center of gravity, T is the duration of the acceleration pulse, and dt is the time interval in seconds. The SI value is a function of the duration of the resultant translational acceleration in assessing head injury risk [1, 3, 25].

Another method of measuring head impact response is with HIC. HIC has been used by the automotive injury in assessing automotive crashes since 1975. HIC is a variation of SI to assess head impact responses. This value is calculated by:

$$\mathrm{HIC} = \{(t_2 - t_1)[\int_{t_1}^{t_2} a(t)dt/(t_2 - t_1)]^{2.5}\}_{\max}$$

Where a(t) is the resultant translational acceleration of the head center of gravity and a standard value of 15 ms is used for (t_2-t_1) [1, 3].

The problem with both SI and HIC is that it only takes into account the resultant translational acceleration as well as duration. Although NFL studies have shown that linear acceleration is most strongly correlated with acquiring a mTBI, other factors associated with head impact biomechanics contribute to mTBIs. There exists a great need to establish a new head injury tolerance assessment that takes into account resultant linear and rotational acceleration, location of impact, HIC and SI values, and impact duration into one representative model. Numerous studies are underway in accomplishing this task of constructing new head impact tolerance models [42].

3.7. Neuropsychological Testing

Many recent advancements have been made in evaluating and monitoring concussions with the use of neuropsychological testing, and it is widely used in other contact sport such as ice hockey [12]. As of 2007, the NFL has mandated the use of a neuropsychology program to assess head injuries in athletes [36]. This program provides information associated with the recovery period of the athlete based upon baseline data from pre-injury performance. It incorporates information about the neurocognitive processes like attentional, memory, and cognitive processing speed. Another program that is being used by the NFL and other sports is the ImPACT Neuropsychology computer program. This program contains six different neuropsychological tests to evaluate cognitive functions (attention, memory, processing speed, and reaction time) of the athlete. These computerized tests are taken by the players the day after the injury occurred, and they measure the neurocognitive deficits of the athlete after experiencing a head injury. Figure 3.6 shows the measures used to evaluate the neurocognitive performance of the athlete during the ImPACT test [12, 16, 36].

Test name	**Neurocognitive domain measured**
Word memory	Verbal recognition memory (learning and retention)
Design memory	Spatial recognition memory (learning and retention)
Xs and Os	Visual working memory and cognitive speed
Symbol match	Memory and visual-motor speed
Color match	Impulse inhibition and visual-motor speed
Three letter memory	Verbal working memory and cognitive speed
Symptom scale	Rating of individual self-reported symptoms
Composite scores	**Contributing scores**
Verbal memory	Word memory (learning and delayed), symbol match, memory score, three letters memory score
Visual memory	Design memory (learning and delayed), Xs and Os (percent correct)
Reaction time	Xs and Os (average counted correct reaction time), symbol match (average weighted reaction time for correct responses), color match (average reaction time for correct response)
Visual motor	Xs and Os (average correct distracters)
Processing speed	Symbol match (average correct responses), three letters (number of correct numbers correctly counted)
Impulse control	Xs and Os (number of incorrect distracters), color match (number of errors)

Figure 3.6 Typical measures used in the ImPACT Test to assess neurocognitive performance of an athlete [16].

CHAPTER FOUR

BIOMECHANICS OF THE AMERICAN FOOTBALL IMPACT

4.1. Types of Helmet Impacts

There are three types of football impacts: helmet-to-ground, helmet-to-helmet and helmet-to-body. Helmet-to-ground involves the struck players' helmet contacting the field upon impact; helmet-to-helmet involves the struck players' helmet contacting the striking players' helmet upon impact and this can include contact with either the facemask or helmet shell region; and helmet-to-body involves the struck players' helmet contacting the body of the striking player including the torso, arm, leg, knee, or hip [1, 3].

According to a study performed by Pellman et al., 182 cases of powerful open-field NFL game impacts were analyzed. From the analysis, helmet-to-helmet impacts were the most common impact in the open-field NFL impacts at 61.5% of impacts followed by helmet-to-body at 22.4% of impacts, and finally helmet-to-ground at 16.1% of impacts. Of these 182 impacts, for the struck player, 70.7% were received to the shell of the helmet, whereas the remaining 29.3% were to the facemask of the helmet [1, 3]. These 182 cases were further analyzed by reconstructing 31 of the NFL collisions, 25 of which resulted in concussions. From the 25 impacts that resulted in concussions, 88% resulted from helmet-to-helmet impacts, and the remaining 12% resulted from helmet-to-ground impacts. One limitation of this study was that helmet-to-body impacts were not reconstructed and evaluated [1].

4.2. Typical Collision Response

A typical impact involves a striking player contacting another player by driving his body through the struck player generating impact energy that is transferred to the outer shell of the helmet. In order to avoid a single concentrated load, the impact energy is dissipated throughout the polycarbonate shell. The impact energy is then transferred to the padding within the helmet where the padding compresses to a certain extent depending upon the magnitude of the impact. The remaining impact energy is transferred to the player’s head causing the head and neck to rotate both laterally and rotationally [1]. Due to each player having a different role on the field, this puts certain positions at varying risks of head impact injury. According to Levy et al, head impact injury risk is related to a variety of variables that include: the position, the impact velocity, the field surface composition and condition, type of helmet, inconsistency in player anatomy, previous injuries sustained by the player, weather, and style of play [24].

A typical football impact lasts about10 ms. During the collision event, between the time of 6-8 ms is when the struck player experiences the greatest impact force and head acceleration. By 10 ms, the time at the end of the impact, the head has undergone a rapid change in velocity and therefore, there begins to be a rapid change in head displacement and rotation causing deformation in the neck to occur. From the study conducted by Pellman et al. of reconstructed NFL impacts, at 10 ms, there was a translational displacement of 20.2 ± 6.8 mm and a rotational displacement of 6.9 ± 2.5 ° compared to at 20 ms, there was a translational displacement of 87.6 ± 21.2 mm and a rotational displacement of 29.9 ± 9.5°. See Table 4.1 for a summary of the results from this study [1]. It can be seen that there was a large displacement of the head within 10 ms. [3].

Table 4.1 Translational and rotational displacement changes of the struck player at 10 and 20 ms after impact [1].

	10 ms	20 ms
Translational Displacement	20.2 ± 6.8 mm	87.6 ± 21.2 mm
Rotational Displacment	6.9 ± 2.5 °	29.9 ± 9.5°

Due to the fact that the mechanism causing concussions are so poorly understood, there exists a need to have multiple measures to define the exposure of a head impact. There are several biomechanical responses and a variety of factors that influence the head response upon impact. These include the magnitude of translational and rotational head acceleration from the head center of gravity, the frequency of head impacts, the location of impact, and the collective history of head impacts to a specific player [3]. Translational and rotational acceleration of the head depend upon the magnitude and direction of the impact received as well as the head-and-neck musculoskeletal structures and anatomical features of the struck player [1]. It has been found from several studies that concussions are most strongly correlated to translational acceleration which is the reason why

NOCSAE standards primarily focus on measuring and assessing the response of helmet performance due to translational acceleration. However, rotational acceleration does play a significant role in head response injury and concussion occurrence due to impacts. Lissner et al. established a baseline tolerance curve relating the peak linear acceleration to duration due to impacts based upon dropping cadaver heads onto a steel plate [3].

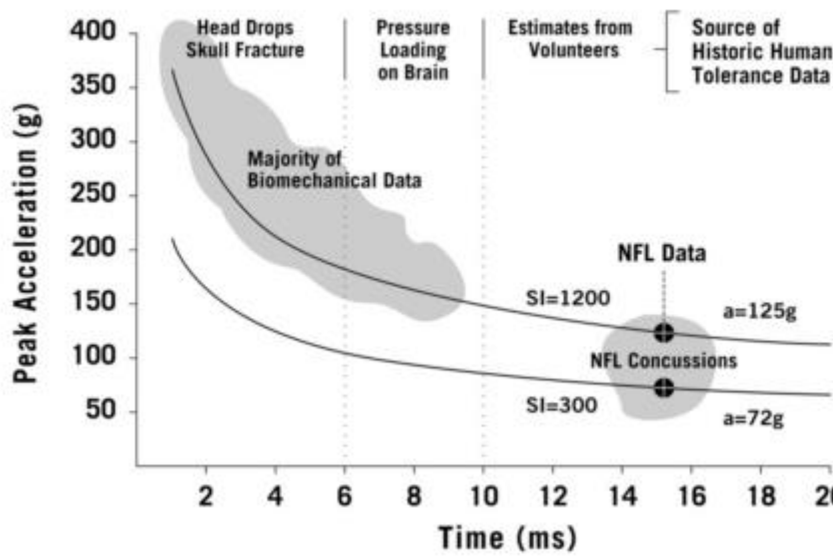


Figure 4.1 Wayne State University Concussion Tolerance Curve established by Lissner et al. based upon results of drop impact testing of cadaver skulls on steel plates [3].

When looking at rotational acceleration, the primary three-dimensional axes system that is used to evaluate the movement of the head about the x, y, and z axes is the coronal, transverse, and sagittal planes where the head center of gravity (CG) is at the location (0, 0, 0). The x-axis is on the coronal plane with the anterior direction defined as positive and the posterior direction defined as negative. The y-axis is on the transverse plane with the lateral direction to the left defined as positive. The z-axis is on the sagittal plane with the superior direction defined as positive and the inferior position defined as negative [1, 2].

Initially when looking at the primary response upon impact, the head acceleration of the struck player is tremendously greater than the striking player. This is due to the difference in momentum between players. Because the striking player has a greater effective mass, the struck player experiences a greater head acceleration upon impact [1, 3].

There are three main factors that dictate the concussion risk of the struck player upon impact. These include impact force, head acceleration, and change in head velocity. In order to calculate the impact force of the struck player, the head inertia force and neck compression forces as well as the resultant head acceleration of the striking player's head must be taken into account. Directly upon impact, there is a quick increase in the change in head velocity. This rapid increase in velocity leads to displacement and rotation of the head leading to strain and deformation in the struck player's neck. The collision between players causes a deceleration of the striking player (assume striking player contacts struck player with a positive acceleration) and an acceleration of the head of struck player (assumes struck player's head has an acceleration of zero prior to impact). The acceleration of the head of the struck player is decreased by the shear and axial forces that develop within the neck with the rapid change in head velocity and bending and rotation [1].

4.3. Influence of Neck Strength

It has been found from numerous studies, that one factor that could be a leading cause in concussion is rotational acceleration which occurs later in the collision biomechanics sequence. Rotational acceleration causes the movement of the head about the z-axis, and it is directly related to neck strength and stiffness. These conclusions are also consistent with animal models that have been constructed and tested, as well as studies performed on knock-out boxing impacts. Pellman et al., found from reconstructed NFL collisions that the greatest force occurring within an impacted player is the neck tension force at 20 ms ranging in values between 1704 ± 432 N. The magnitude of the forces experienced in the neck are dictated by the neck anthropometry, muscle strength, and the stretching and compressing effects of the ligaments and tendons within the neck structure. Therefore, a stronger and stiffer neck has the ability to decrease the resultant rotational head acceleration experienced by the struck player [1]. Previous literature has found that in automobile crashes, the neck undergoes 5 N/mm of extension when a stationary, relaxed head and neck are subject to whiplash. Comparing this to football collisions, the neck stiffness values are tremendously greater at values close to 80 N/mm [1, 43].

Previous literature has shown that adolescents and females have a greater risk of receiving a concussion than male adults [1, 16, 44]. It is hypothesized that this is due to the relatively weak neck structure musculature of adolescents and females compared to the male counterpart. Due to the weaker neck musculature, this puts the young athlete and female at a higher susceptibility to a rapid change in head velocity and therefore head and neck displacement and rotation. This could be a direct correlation to the prevalence of a greater number of concussions in the young athletes and females [1].

The calculation of the SI and HIC in assessing the possibility of a head injury is directly correlated to the change in head velocity. If the strength of the neck is related to the change in head velocity and head movement and rotation, it can be seen that increasing the strength of the neck will lower the change in head velocity and therefore, decrease the head movement and rotation and therefore lower the HIC and SI values. The data shows that a weaker neck musculature structure leads to a greater change in head velocity upon impact and therefore, a greater change in head displacement, leading to increased strain within the brain. These results reveal the importance of strength training in athletics, specifically, the importance of increasing the strength of the neck muscles [1].

4.4. Event-Type and Skill-level Differences in the Prevalence of Concussion

Numerous studies have been conducted to relate the prevalence of concussion to event-type differences, positional differences, and skill-level differences (youth football, high school football, collegiate football, and professional football). It is important to investigate the effects of head impacts in football due to the number of impacts and severity of impacts that each player sustains over the course of a season. A player can experiences between 520 to 2,000 impacts in one season depending on position played [4, 28].These studies have all been completed using different mechanisms of data collection and analysis leading to varying results between studies.

In a study conducted by Duma et al., head impact accelerations of collegiate football players during practices and games were recorded and evaluated. There were thirty-eight players from the 2002-2003 Virginia Tech (VT) football team that were equipped with the HIT System in conjunction with the SRS System. From this study, 3,112 impacts were obtained: 1,198 impacts that occurred over the course of 10 games and 2,114 impacts that occurred over 35 practices [2].

The results of the study of the VT football team showed that for all the impacts that were recorded, the average peak linear head acceleration was 32 ± 25 G and the average rotational head acceleration was 905 rad/s^2 ± 1075 rad/s^2 about the x-axis and 2020 rad/s^2 ± 2042 rad/s^2 about the y-axis. The value of the peak linear acceleration for the uninjured player was similar in value to 29.2 G which was found by Naunheim et al. from high school football impacts [45]. Of the 3,112 impacts recorded, 89% had a peak head acceleration less than 60 G, and the average HIC and GSI values for all recorded impacts were 26 ± 64 and 36 ± 91 respectively. A summary of the results can be found in Table 4.2 [2].

Table 4.2 A summary of the average results obtained from 3,112 recorded impacts occurring during practices and games for the 2002-2003 VT football season [2].

Average Peak Linear Acceleration	32 ± 25 G
Average Rotational Acceleration (about x-axis)	905 rad/s^2 ± 1075 rad/s^2
Average Rotational Acceleration (about y-axis)	2020 rad/s^2 ± 2042 rad/s^2
HIC	26 ± 64
GSI	36 ± 91

During the 2002-2003 season, there were 5 total concussions that were reported. Only 1 of these concussions was monitored by the HIT and SRS Systems at the time of impact. This concussion occurred at the second impact after a kickoff play when the player was struck and fell backwards to hit the helmet on the ground. There was no loss of consciousness. The player experienced a peak linear head acceleration of 81 G and a rotational head acceleration of 5600 rad/s^2 (about the x-axis) and 5590 rad/s^2 (about the y-axis). The HIC and SI for this concussion impact was 200 and 267 respectively. A summary of the results of the concussed player can be seen in Table 4.3 [2].

Table 4.3 Conditions experienced by a concussed player on the VT football team during the 2002-2003 season [2].

Peak Linear Head Acceleration	81 G
Rotational Head Acceleration (x-axis)	5600 rad/s^2
Rotational Head Acceleration (y-axis)	5590 rad/s^2
HIC	200
SI	267

In comparison to the VT study conducted by Duma et al, a study performed by Pellman et al., a combination of thirty-one impacts that occurred in the National Football League games between 1996 and 2001 were reconstructed. The laboratory reconstructions were specifically chosen based upon 182 cases of video footage that were available from impacts that occurred throughout the season. Of the 182 impacts that were available on video footage, only 31 cases were chosen to be reconstructed. From the 31 reconstructed impacts, 25 resulted in diagnosed concussions [1, 3].

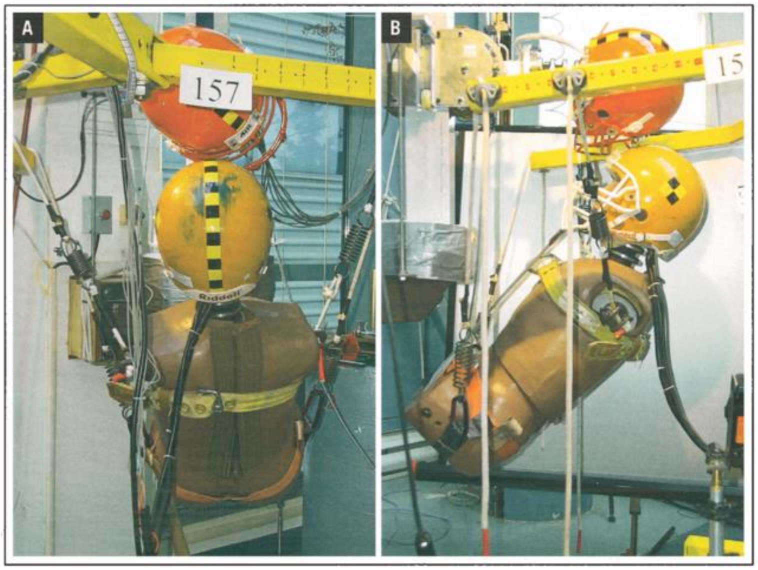


Figure 4.2 Equipment used for the reconstruction of NFL game impacts from video analysis using Hybrid III head, neck, and torso assemblies [3].

In order for an observed impact to be reconstructed, the impact needed to have two clear views of the impact from different locations in order to find the three-dimensional impact velocity, orientations, and helmet kinematics of the impact. Two Hybrid III male crash test dummies were used as the reconstruction models equipped with nine linear accelerometers in a 3-2-2-2 configuration at the Hybrid III head center of gravity [1, 3].

From the NFL video reconstructions, it was found that a typical concussed player experienced an average head impact velocity from a striking player at 9.3 ± 1.9 m/s (20.8 ± 4.2 mph) and a peak head acceleration of 98 ± 28 G at 118 J (66-184 J) of impact energy which was significantly greater than the uninjured (did not experience concussion) struck player. These values compared to an uninjured struck players who experiences a peak head acceleration of 60 ± 24 G at 57 J (35-85 J) of impact energy [1, 2]. Both the injured and uninjured struck player undergo a rapid change in head velocity upon impact which is 7.2 ± 1.8 m/s (16.1 ± 4.0 mph) and 5.0 ± 1.1 m/s (11.2 ± 2.5 mph) respectively. A typical duration of impact that a concussed player experienced was 15 milliseconds, and the baseline HIC limit and SI limit for a player who experienced a concussion was found to be 250 and 300 respectively. From prior literature of military studies, acceleration tolerance was estimated to be between 42-80 G for a 15 millisecond head impact. Comparing these values to other impacts, a car colliding with a pole typically has a 4 ms duration, whereas adding airbags to the car leads to a 40 ms duration between the airbag and human subject upon crashing [1, 3]. Increasing the duration of impact in car collisions has been effective in decreasing the severity of injury; hence why evaluating duration is important in assessing football impacts.

Table 4.4 A summary of the average results obtained from 31 reconstructed NFL impacts during games occurring between the 1996-2001 seasons [1, 3].

	Struck Player (Injured)	Struck Player (Uninjured)
Peak Head Acceleration	98 ± 28 G	60 ± 24 G
Change in Head Velocity	7.2 ± 1.8 m/s (16.1 ± 4.0 mph)	5.0 ± 1.1 m/s (11.2 ± 2.5 mph)
Impact Energy	118 J (66-184 J)	57 J (35-85 J)

4.5. Geometry of the Football Helmet

When looking at specific locations of impact on a helmet, Pellman et al. found that impacts that occurred to the facemask led to significantly greater head rotations due to the increased moment arm about the z-axis and head CG compared to impacts that occurred to the shell of the football helmet. The facemask projects roughly 160 mm forward of the head CG. With the moment arm increasing with impacts to the facemask, this leads to greater head rotational accelerations and could be a correlation to increasing the risk of a concussion. This could be used to show how impacts to the chin could increase the risk of concussion due to its increased moment arm as well. A typical chin projects forward 95 mm from the head CG. Data from this study can be correlated to data collected on boxing knockouts to explain why most to impacts to the chin lead to loss of consciousness. This data should be taken into account when designing football helmets with a large facemask [1]. Also, Crisco et al. conducted a study and found that impacts to the top of the helmet had the greatest magnitude of peak linear acceleration due to the thickness of the helmet at this location and the decreased moment arm dictating rotation about the z-axis at this location [28].

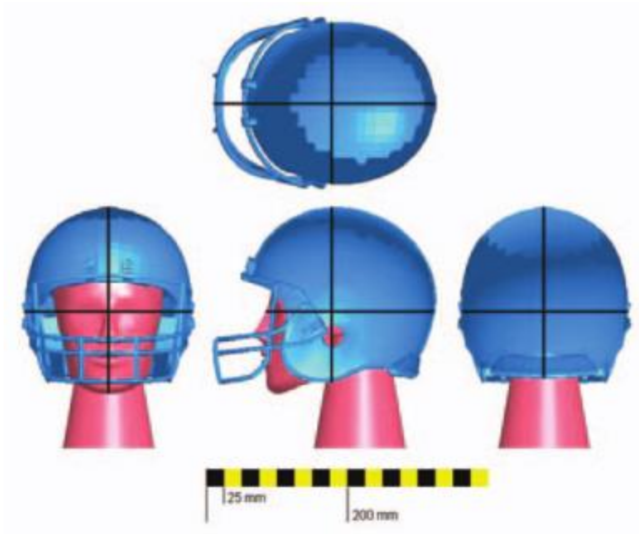


Figure 4.3 Model of a football player's head equipped with a helmet showing the CG of the head in relation to the dimensions of the facemask [1].

Comparing the two studies performed by Duma et al. and Pellman et al., there are differences that must be reconciled between each study. Duma et al., looks at the analysis of collegiate level football players and uses real-time measurements compared to Pellman et al., who looks at professional football players using reconstructed video analysis. It must be noted the differences and discrepancies between real-time analysis and video analysis. Video analysis does not provide the most accurate measurements in terms of velocity of the striking and struck player. When using video analysis, this is reconstructed data using a Hybrid III head, neck, and torso assembly. The Hybrid III head structure is not completely representative of a human head structure due to the fact that the head is made of vinyl and has a fixed jaw. It must be noted that precautions were taken to help make the hybrid III assembly as realistic as possible. [3]. Also, there could be discrepancies due to the fact that different skill levels were being compared. Duma et al.

utilized collegiate football athletes compared to Pellman et al. who utilized NFL athletes. It must be noted that there are differences in skill level, strength, and speed between the divisions. Another difference that must be taken into account is that Duma et al. recorded and analyzed all head impacts that occurred throughout practice and games, whereas Pellman et al., only analyzed serious open field impacts. This could be a reason for the discrepancy in peak linear accelerations between both studies. A final reason for discrepancy in data could be due to the fact that concussions are underreported. Often times, athletes do not realize that they have sustained a concussion and do not report it. One study found that only 47.3% of high school football athletes reported a concussion following the impact event, and only 23.4% of collegiate football athletes could recognize his injury symptoms as related to concussions [2, 46].

4.6. Positional Differences in the Prevalence of Concussion

Mihalik et al. investigated the positional and event type differences for a NCAA football team during the 2005-2006 season. Seventy-two players were equipped with the HIT System connected to the SRS System, and the representative positions were 22 offensive linemen, 13 defensive linemen, 12 defensive backs (cornerbacks and safeties), 9 linemen, 12 offensive backs, and 5 wide receivers. Any acceleration that was picked up that was below 10 G were not included in the data analysis because these accelerations are typical of running, standing up, etc. Throughout the course of two seasons, 82,026 head impacts were recorded, and 57,024 impacts qualified as over 10 G and could be used in the study [4].

The results of the study done by Mihalik et al. showed that there is a significant difference between each position. It was found that typical peak linear acceleration sustained by collegiate football players ranged from 21-23 G. Looking at the linemen, the offensive linemen receive higher acceleration head impacts compared to the defensive linemen and defensive backs [4].

Table 4.5 Average peak linear acceleration values for the linemen in during the 2005 and 2006 season of a collegiate level team [4].

	Offensive Linemen	Defensive Linemen	Defensive Backs
Average peak linear acceleration	22.89 ± 1.79 G	21.56 ± 1.76 G	21.02 ± 1.78 G

Comparing the number of impacts per position, Mihalik et al. found that offensive linemen and defensive linemen sustained the most impacts with the lower values of average peak linear acceleration. This data is consistent with Crisco et al. [28]. Offensive backs were the most likely position to undergo an impact greater than 80 G compared to the other positions, whereas Crisco et al. found that running backs received the impacts of the greatest magnitude [4].

Position	Frequency of recorded impacts	Mean (± standard deviation) linear acceleration (g) of recorded head impacts
Offensive linemen	20,256 (35.52%)	22.89 ± 1.79
Offensive backs	7066 (12.39%)	22.93 ± 1.83
Defensive linemen	12,540 (21.99%)	21.56 ± 1.76
Defensive backs	8767 (15.37%)	21.02 ± 1.78
Linebackers	5892 (10.33%)	22.67 ± 1.81
Wide receivers	2503 (4.39%)	22.19 ± 1.83
Total	57,024	22.25 ± 1.79

Figure 4.4 The frequency of impacts and average peak linear accelerations recorded by player position during the 2005 and 2006 season of a collegiate level team [4].

Mihalik et al. also looked at event differences comparing both helmet-only practices and full-contact practices verse games. The data showed that impacts sustained in practice were of greater magnitude than those impacts sustained in games. There was also a greater amount of impacts received in practice verse games. This information raises attention and should be investigated further because most concussions happen during game impact events [4]. The results of this study need to be taken into account by coaches and medical personal when designing and monitoring practice plans.

When looking at the differences in magnitude between the data of the peak linear acceleration found by Mihalik et al. (21-23 G) verse Duma et al (32 ± 25 G), differences in data acquisition must be taken into account. Duma et al. did not filter the data from impacts under 10 G like Mihalik et al. which is the reason the study results in a more broad range of data. It is also important to note that, Duma et al. used the HIT accelerometer system on 38 different players, and the accelerometer units were not kept consistent between players while recording the data [2, 4].

Casson et al., compared the results of two separate studies over a six year period from 1996-2001 and 2002-2007. These studies served to compare the prevalence of concussion occurrence and signs and symptoms between these two periods. It was found that there is similarity in the two six-year period studies, however, some differences did occurr. There were fewer cases of mTBI throughout the second six year period, but the results were not statistically significant. Also, prevalence of concussions in tight ends increased in the second 6-year period. [36]. When looking at ways to decrease the prevalence of concussion, some have suggested that the stiffness of the top crown portion of the football helmet should be reduced as well as decreasing the mass of the helmet [12].

CHAPTER FIVE

CHARACTERIZATION OF FOOTBALL HELMET MATERIALS

5.1. Current Football Helmet Materials

An engineered polycarbonate (PC) blend is the most common material that the external shell of the football helmet is made of and is composed of a mixture of mainly polycarbonate with the addition of polyethylene terephthalate (PET) [20, 26]. PC is an amorphous thermoplastic polymer that is known for having stabilized mechanical properties over a range of temperatures. It is a ductile material with significant mechanical strength. PC is capable of undergoing a wide variety of processing techniques including injection molding and thermoforming [5]. See Table 5.1 for the physical properties of PC.

Table 5.1 Physical properties of PC [5].

Glassy Temperature Range	135-140°C
Melting Temperature Range	220-260°C
Thermal Degradation Range	280-320°C
Ultimate Tensile Stress	60 MPa

Depending on the helmet chosen by the player, the inner foam padding is made of either vinyl nitrile (VN) foams, expanded polypropylene (EPP), or thermoplastic polyurethane (TPU) [20, 26, 47]. The internal foams absorb most of the impact energy by undergoing plastic deformation [27]. TPU is a three dimensional engineered material that is anisotropic and inhomogeneous. The VN material is isotropic and homogeneous [26]. There have been several issues with the performance of the internal foam padding properties changing significantly due to changes of temperature inside the helmet. However, TPU is beneficial because it absorbs impact steadily over a variety of temperatures compared to other foam paddings on the market [47] .

Studies have been performed by Post et al. comparing the performance of VN foams compared to TPU foams in football helmets. Tests were performed using a linear actuator containing a piston impacting arm. The Hybrid III dummy was impacted at a velocity of 7.5 m/s. This arm impacted a Hybrid III dummy equipped with a football helmet. From the study, it was concluded that engineered materials such as TPU may have a more beneficial use in the football helmet related to impact absorption and dissipation. Results show that VN is capable of dissipating linear acceleration well, and because NOCSAE certification tests only take into account linear acceleration, this is why helmets containing VN foam padding perform well under certification tests. VN foams however, are limited in terms of rotational acceleration energy absorption due to limitations with alterations in liner thickness and density. Engineered materials, such as TPU, are better able to absorb rotational impact energy compared to VN foam padding. This is because engineered material’s properties such as the stiffness, geometry, and constituent materials may be enhanced to better dissipate rotational energy. Overall, from the study, it was concluded that anisotropic inhomogeneous materials are better able to absorb rotational energy compared to isotropic homogenous materials [26].

In a follow-up study by Post et al., the performance of VN foams to EPP foams were compared. Results showed that both VN and EPP were relatively equal in terms of decreasing the linear acceleration upon impact from the same linear actuator containing a piston impacting arm from the study described above. However, the difference was related to the response of each foam when subject to rotational acceleration. VN performed better when subject to impacts associated with rotational acceleration [32, 48]. This is due to the fact that VN foams undergo shearing and torsion better than EPP upon impact [26].

Other important layers of the football helmet include the internal foam, faceguard, and plastic facemask. The most internal layer of the football helmet is the air liner with the primary function of improved fit and comfort. This layer of the football helmet is made of a thermoplastic polyurethane (TPU) material [47]. The faceguard of the football helmet can either be made of stainless steel, carbon steel, or titanium. Titanium is more advantages over carbon steel because it is much more lightweight. The titanium material can be up to 60% lighter than the standard carbon steel faceguards [47].

5.2. Composite Materials

According to Dehkordi et al., simply put, composites are “materials made by combining two different types of fibers in a common matrix” [49]. According to Chawla, author of Composite Materials: Science and Engineering, a more complex definition entails, a composite is a material that must satisfy the following three conditions:

1. It is manufactured.
2. It consists of two or more physically and/or chemically distinct, suitably arranged or distributed phases with an interface separating them.
3. It has characteristics that are not depicted by any of the components in isolation [7].

Polymer composite materials have been around since the 1960s. One benefit of composite materials in the field of energy absorption is they have the capabilities of being designed to be stronger and stiffer while decreasing the weight compared to other current raw materials. This makes composites attractive in the helmet shell market. Composites are very beneficial for use in a variety of applications because they can be specifically designed to meet the specific needs of different applications by altering the independent material properties by combining several fibers [7, 49].

When designing composite materials, three important factors must be taken into account in order to achieve the desired properties. The first factor is that a smaller diameter fiber with respect to its grain size is more beneficial because this gives a lower probability of having defects within the fiber. This increases the strength of the fiber material compared to the material in bulk form. The second factor important in designing composites is to have a high length/diameter ratio. This high ratio makes it capable to transfer the majority of large loads to fibers that are stiffer and stronger by way of the matrix when subject to impact. The third and final factor that is important in the design of composites is for the fibers to have high flexibility. Flexibility is crucial in manufacturing the composite, and it allows for a range of different manufacturing techniques to be applied to construct the composite [7].

Composites are made up of three regions: the fibers, the matrix, and the interphase region. The fibers within a composite are responsible for bearing a large amount of the load that the composite experiences. The choice of which fibers are used in a composite material greatly influence the strength and stiffness of the overall material. The next component in a composite is the matrix. The key responsibility of the matrix is to protect the fibers, align and stabilize the fibers, and to transfer stress from impact between fibers. Strength and stiffness of the matrix compared to the individual fibers are significantly less for the former. The interphase region is the area between the fibers and the resin. It is of vital importance to ensure that there is the best adhesion between the resin and fibers in this area [17, 50].

Low-velocity impacts are defined as those impacts where the velocity used is sufficient enough to allow the complete composite structure to respond to the impact event. Typical impact velocities range between 1-10 m/s. This leads to deformation within the entire structure. This is different compared to high-velocity impacts where the velocity that the composite experiences is so great that the duration of impact is not long enough for the entire structure to undergo damage. Damage that is seen under high-velocity impact is localized at the point of impact [17]. For the purpose of this thesis, low-velocity impacts were used because these velocities are more representative of the typical football hit.

One downside of composites is that upon impact, damage can be seen on the surface, however, there is significant damage that occurs internally. Composites are known to be brittle materials, meaning that energy is absorbed elastically through deformation and failure mechanisms internally; however, composites do not undergo much plastic deformation [17].

The internal failure mechanisms that composites experience sacrifice the integrity of the strength of the composite. There are numerous internal failure mechanisms including: matrix damage (intralminar matrix cracking, longitudinal matrix splitting, debonding), delamination, fiber fracture/failure, and penetration [17, 50]. Matrix damage is failure that occurs due to the fibers being subject to tension, compression, and shear forces. This cracking is typically the first type of internal failure that happens upon impact (Figure 5.1). Debonding is a type of matrix cracking where the fibers and matrix separate [17].

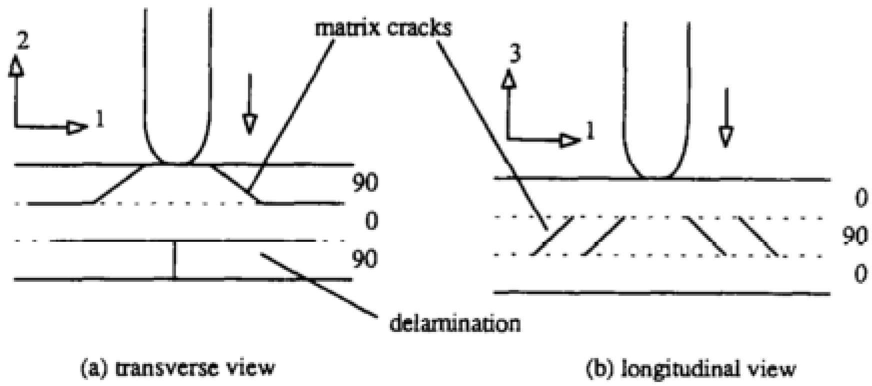


Figure 5.1 Matrix damage that occurs initially upon impact [17].

A second type of internal failure mode is delamination. Delamination occurs due to interlaminar stresses, and it is when there is a crack in the resin space between layers (plies) of the composite. Another type of failure is fiber failure. Fiber fracture is caused by fibers breaking when subject to tension forces and fibers buckling when subject to compression forces. This mode of failure occurs later in the process due to damage caused by the impactor. The final mode of failure is penetration. This occurs when the impactor pierces through the composite [17].

Hybrid composite materials have proven beneficial in a variety of applications due to their exceptional strength, decreased weight, good fatigue life, and corrosion resistance [51]. Composites have proven attractive for use in the outer shell of football helmets compared to the current thermoplastic material used because of its dominate performance under impact conditions. Composites are able to absorb and dissipate energy through deformation and internal failures. Upon impact, the composite undergoes a variety of different failure mechanisms including interlaminar and intralaminar damage like fiber breakage, matrix cracking, and delamination. One major downside of the use of composites for the outer shell of the helmet is its cost to manufacture compared to the current materials [27].

There are a variety of fibers that were used in the flat panel composite specimens used in testing. Fibers were either co-woven or commingled. Co-woven fibers involved weaving multiple fibers into one fabric ply (Figure 5.2); whereas, commingled fibers involved combining several raw materials into a single fiber to be woven into a fabric (Figure 5.3) [18]. These fibers include the Innegra H fiber, Innegra S fiber, basalt, aramid (Kevlar), carbon, and S and E glass. Each fiber has its advantages and disadvantages.

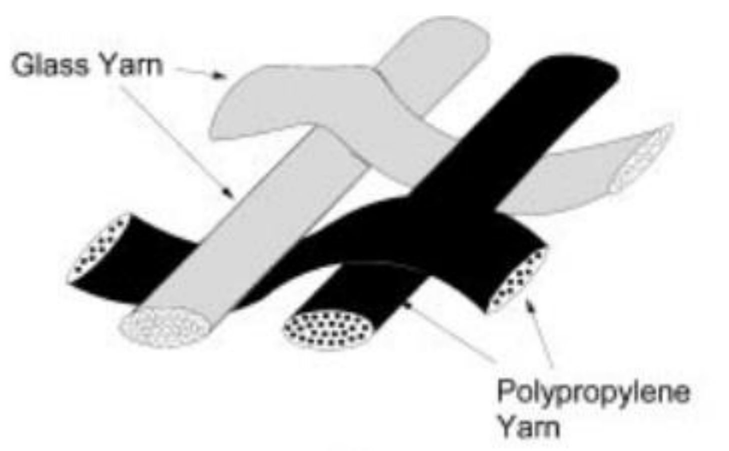


Figure 5.2 Representation of a fabric composed of several yarns to make a co-woven hybrid [18].

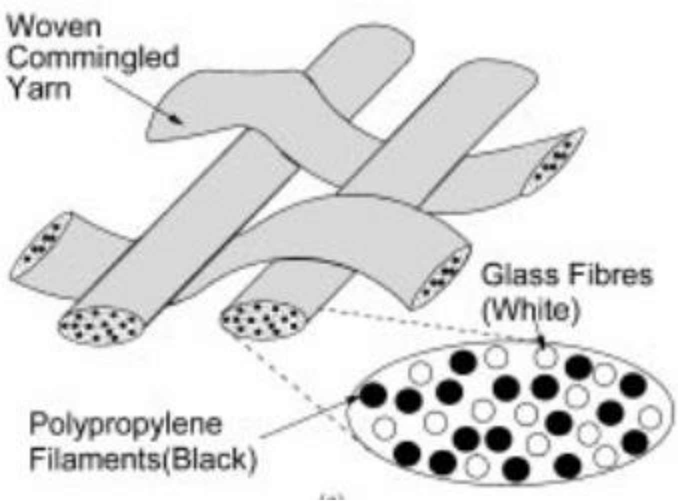


Figure 5.3 Representation of a fabric made up of a commingled hybrid yarn [18].

Innegra H and Innegra S

The Innegra S Fiber is a type of highly crystalline polypropylene fiber (see Figure # for chemical structure) with a density of 0.84 g/cm^3. The high specific strength, stiffness, and excellent fatigue characteristics of polypropylene fibers have proven to be beneficial in the aerospace, automotive, and marine industries. Literature has shown that the use of polypropylene in applications requiring energy absorption has proven true [52]. Specifically, the Innegra fiber's beneficial properties include that it is hydrophobic, tough, and durable. It has low elongation and low creep. The Innegra H Fiber is a hybrid yarn made up of Innegra S and other fibers such as basalt, carbon, and glass. Innegra H Fibers have improved properties over the Innegra S Fibers including increased durability and impact resistance and decreased chance of catastrophic failure. Both types of fibers are currently available in two colors: white and black. Currently, these fibers can be used in a wide range of applications including the sporting industry, luggage, aerospace, military, and ballistics. Innegra fibers are currently being used in products on the market such as: Bauer goalie hockey sticks, Head tennis rackets, Mirage Kayaks, AT whitewater paddle boards, and SUP paddles. Due to the proprietary nature of both fibers, specific technical information cannot be released regarding the composition of the Innegra fibers; however, material properties can be seen in Table 5.2 [6, 53, 54].

Table 5.2 Physical properties of Innegra [6].

	Density [kg/m^3]	Tensile Strength [MPa]	Modulus [GPa]	Elongation at Break [%]	Cost
Innegra	0.84	667	16	9.5	+++

Basalt

Basalt fibers are inorganic materials that offer a moderate strength, modulus, and thermal and chemical properties. The density of basalt is 2700 kg/m^3. However, one issue with basalt fibers is that they do not demonstrate the best responses when subject to impact [49]. Comparing glass and basalt fibers, glass and basalt fibers both have comparable strength and moduli; however, basalt fibers exhibit better thermal properties [49, 55]. The material properties of Basalt can be seen in Table 5.3 [6].

Table 5.3 Physical properties of Basalt [6].

	Density [kg/m^3]	Tensile Strength [MPa]	Modulus [GPa]	Elongation at Break [%]	Cost
Basalt	2.7	4840	89	3.2	++

Aramid (Kevlar)

Aramid fibers encompass a wide class range of fibers. These fibers are highly crystalline with strong covalent bonds and are anisotropic in nature. The US Federal Train Commission defines an aramid fiber as “a manufactured fiber in which the fiber-forming substance is a long-chain synthetic polyamide in which at least 85% of the aramid linkages are attached directly to two aromatic rings.” The chemical composition of a generic aramid can be seen in Figure 5.4. The composition of aramid fibers entail a para-substituted aromatic rings. This allows for the material to be rigid. A specific aramid is Kevlar which contains a ring structure. Several properties of aramids include poor solubility and high glass transition temperatures. Other mechanical properties can be seen in Table 5.4. Several limitations of aramid/Kevlar fibers include that they can only be used in low temperature ranges (less than 150°C), exhibit poor performance when subject to compression conditions, and they are relatively expensive compared to other fibers such as basalt. The compression strength of Kevlar is significantly less than its tensile strength. Major benefits of aramid fibers are that it demonstrates exceptional vibration-damping characteristics as well as exceptional impact resistance and tensile strength and modulus [7, 55]. A list of material properties can be found in Table 5.4.

Table 5.4 Physical properties of Kevlar [6].

	Density [kg/m³]	Tensile Strength [MPa]	Modulus [GPa]	Elongation at Break [%]	Cost
Aramid	1.44	2400-3600	60-120	2.2-4.4	++++

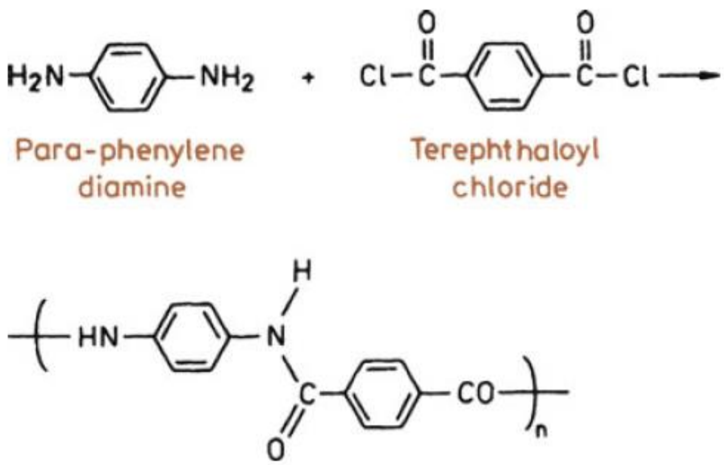


Figure 5.4 Chemical composition of an aramid fiber [7].

Table 5.5 Physical properties of aramid/Kevlar fibers (Note: Kevlar 49 is mainly used in the sports market) [7].

Property	K 29	K 49	K 119	K 129	K 149
Density (g/cm^3)	1.44	1.45	1.44	1.45	1.47
Diameter (μm)	12	12	12	12	12
Tensile strength (GPa)	2.8	2.8	3.0	3.4	2.4
Tensile strain to fracture (%)	3.5–4.0	2.8	4.4	3.3	1.5–1.9
Tensile modulus (GPa)	65	125	55	100	147
Moisture regain (%) at 25 °C, 65 % RH	6	4.3	–	–	1.5
Coefficient of expansion (10^{-6} K^{-1})	−4.0	−4.9	–	–	–

[a]All data from Du Pont brochures. Indicative values only. 25-cm yarn length was used in tensile tests (ASTM D-885). *K* stands for Kevlar, a trademark of Du Pont

Carbon

Carbon fibers can exist in several crystalline forms. The most common crystalline form that carbon exists in is in graphite form (Figure 5.5). In graphite form, the material is anisotropic with a Young's modulus of 1,000 GPa. Because carbon fibers can exist in so many different forms, carbon fibers have a range of properties. The density can range between 1.6-2.0 g/cm^3, and the tensile and Young's modulus can vary based upon the manufacturing technique used to produce them. It is important to note that carbon fibers have increasing strength as the diameter of the fiber decreases [7]. Material properties of Carbon can be found in Table 5.6.

Table 5.6 Physical properties of carbon [6].

	Density [kg/m^3]	Tensile Strength [MPa]	Modulus [GPa]	Elongation at Break [%]	Cost
Carbon	1.78	5313	292	1.8	++++

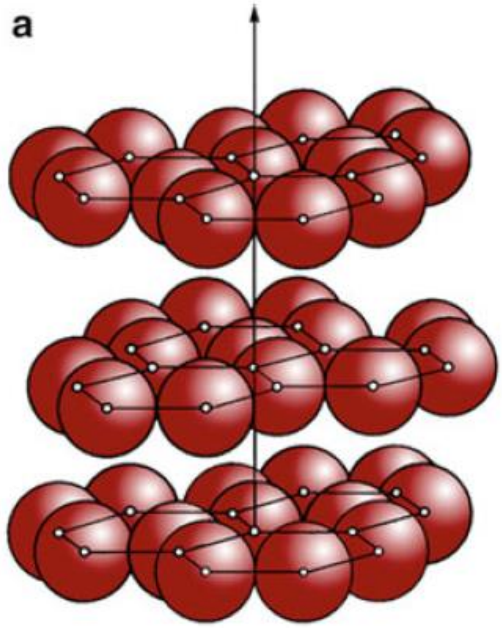


Figure 5.5 Schematic of the graphite crystalline structure of carbon [7].

S and E Glass

Silica based glass fibers (S Glass) and Electrical glass (E glass) are two different types of fibers present in the composite panels fabricated by Innegra Technologies and B&W Fiberglass. S glass is composed of roughly 60% SiO_2 with other impurities such as calcium, boron, sodium, and aluminum, and the properties of S-glass vary and depend on the composition of the impurities within S-glass. Both E glass and S glass are amorphous (see Figure 5.6 for the structure of amorphous glass).

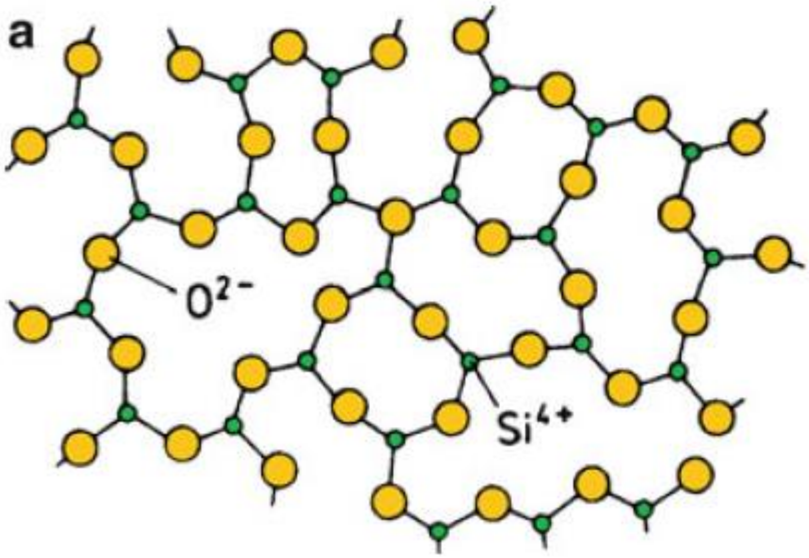


Figure 5.6 Schematic showing the amorphous composition of glass fibers [7].

E glass is known for having good electrical conduction properties. Both types of glass fibers can be fabricated in numerous ways including in chopped strands, continuous yarns, roving, and fabric (see Figure 5.7) [7].

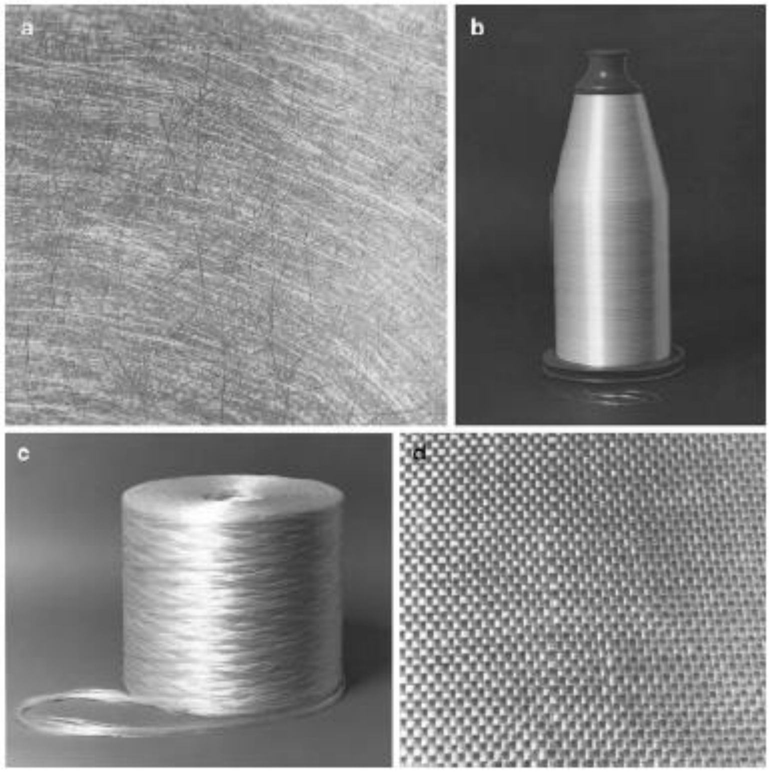


Figure 5.7 Different types of glass fibers produced from different manufacturing techniques (a: chopped strands, b: continuous yarn, c: roving, d: fabric) [7].

E-glass is beneficial because it has substantial strength for its relatively low density as well as being cost effective. See Table 5.7 for properties of E-glass and S-glass. One disadvantage is that it has a low Young's modulus, therefore these fibers are easily fractured upon impact [7].

Table 5.7 Physical properties of E-glass and S-glass [6].

	Density [kg/m^3]	Tensile Strength [MPa]	Modulus [GPa]	Elongation at Break [%]	Cost
E-glass	2.54	2600	72	4	+
S-glass	2.48	4800	85	5.5	+++

There are several disadvantages of glass fibers in general. The first disadvantage is that when subject to moisture, the strength of these fibers decreases significantly. Another disadvantage of glass fibers is that these materials are prone to static fatigue. Static fatigue occurs when a load applied for a long period causes tremendous weakening and eventually fracture in the material. For these reasons, glass fibers are mainly used as a reinforcement fiber alongside other materials [7].

CHAPTER SIX

REVIEW OF LITERATURE FOR THE DEVELOPMENT OF TESTING METHODS FOR FLAT PANEL COMPOSITE TESTING

There are is an overabundance of studies being performed on composite specimens. Each study using different testing methods, parameters, and instrumentation set-ups to conduct these impact tests on flat panel composite specimens. In the following sections, key studies are highlighted for their test methods used on testing of composite specimens that helped aid in the development of the protocol used in the work presented in this thesis.

Hosseinzadeh, Shokrieh, and Lessard set out to investigate how the damage characteristics of a composite depend on the fiber makeup of the material. For their study, four different panels were tested: Glass Woven/Epoxy, Carbon/Epoxy, Glass/Carbon, and Woven/Epoxy (Hybrid). The panel samples were all the same dimensions of 270 x 270 mm. However, the thickness of each sample was varied ranging anywhere from 2.4-4 mm in thickness. Each sample also had different densities. The panels were struck with a spherical impactor head at impact energies of 30, 50, and 100 J with a weight ranging from 2.5-5.5 kg. See Figure 6.1 for the impactor structure. Mass was only varied for the impact energy of 50 J, and the results were evaluated. The supporting frame to hold the panels was square with a raised surface. The purpose of having the panel clamped on all four edges was to ensure that the clamping force was uniform on each sides. Figure 6.2 shows the supporting frame used [19].

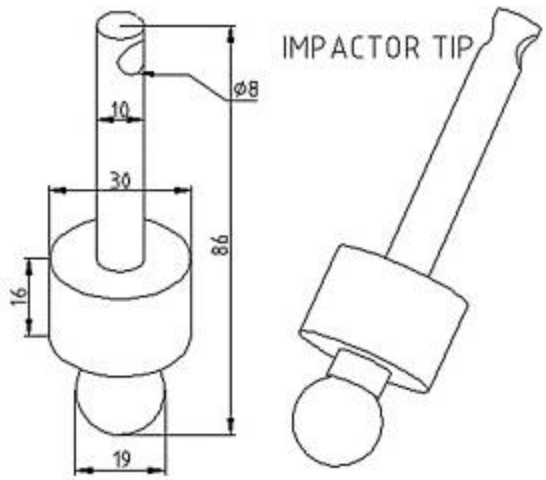


Figure 6.1 Hemispherical impactor tip to be used in all impact tests of flat and curved panel testing [19].

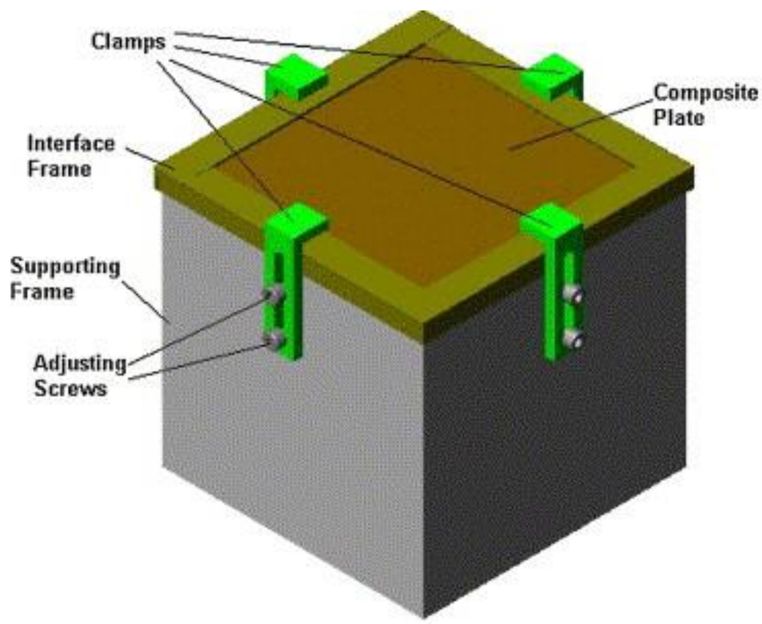


Figure 6.2 Composite panel supporting frame for impact testing of flat panels [19].

Based on the results of the study, Glass/Epoxy demonstrated the best results for all impact energies. However, a downside to the Glass/Epoxy was the increased weight of the panel composition. Carbon/Epoxy and Carbon/Glass/Epoxy (Hybrid) both showed promising low velocity impact responses [19].

Natta investigated the effects of changing the densities of expanded polystyrene (EPS) as the inner foam liner material. In this study, tests were done on both EPS and polycarbonate (PC). The aim of this study was to find the appropriate thickness and density that provided optimal energy absorption for a protective helmet. As the thickness of the EPS is increased, the energy absorption is also increased. However, there are downsides to increasing the thickness of the inner foam liner including weight, manufacturing cost, comfort, and size of the helmet [5].

The experimental method used in the study performed by Natta investigated four different densities of EPS along with PC. Dynamic compression tests were done according to ASTM D3029-84. The falling weight tests were performed on PC and PC/EPS samples of varying density. The drop tower contained a 15.9 mm diameter hemispherical impactor which impacted the samples at impact energies of 28, 40, 55, 75 J. The head mass used was 13.57 kg, and the sample sizes were 100 mm in diameter and 30 mm in thickness. Static compression tests were performed on the EPS and PC according to ASTM D1621-73, and tensile and bending tests were performed according to ASTM D638-86 and ASTM D790-86. It was concluded from this study that a critical parameter in designing a helmet is the EPS density. Once the optimal density was chosen, the impact response did not depend on the thickness of the EPS [5].

Shyr and Pan investigated the damage characteristics of composite laminates following an impact. In order to do so, impact tests were completed with a drop tower. Dynatup Model 8250 was the impact drop test machine used for the experiment. It contained a hemispherical nose (diameter 1.27 cm) indentor with a weight of 47.53kg. Specimen sizes were 10.16 cm x 15.24 cm. Each specimen was secured into a rectangular fixture that contained an open window. Impacts were performed at 8, 16, and 24 J/layer [56].

Lance and Nettles methodology to impact testing in the study of carbon/epoxy composite systems is similar to methods used previously. A Dynatup Model 8200 was used as the drop tower. A 1.27 cm diameter hemispherical impactor with a mass of 1.77 kg was also used to impact the specimens at the center. Each specimen was stabilized by a raised clamping system made up of two aluminum plates that contained open surfaces. Lance and Nettles analyzed the force-time plots, absorbed energy time plots, and maximum force vs impact energy plots which were acquired from the data acquisition software [57].

Numerous other studies comparing the experimental set-up of the flat panel composite testing were reviewed [19, 58–65]. The results of the studies are summarized in Table 6.1. It can be seen that a variety of testing conditions are used on impact testing of composite specimens. When deciding which testing conditions to use, the ASTM Standards must be taken into account. Choosing the desired impact weight depends upon the impact energy and composite panel thickness. The impact energy chosen depends upon the application that the composite configurations will be used in. For football collisions, the concussed and non-concussed player experience impact energies of 118 J and 57 J, respectively [1, 3]. McIntosh et al. found that the protective capabilities of a football helmet no longer function to full capacity when the impact energy experienced by the helmet is greater than 20 J [23].

Table 6.1 Summary of prior literature testing conditions of flat panel composites.

Authors	Impactor Weight [kg]	Impact Energy [J]	Thickness [mm]	Impactor Shape
Soliman et al.	0.63	15, 24, 30, 60, 120	n/a	Hemispherical
Quaresimin et al.	1.84	1.5-10	1.25, 2.4	Hemispherical
Ghelli et al.	1.22	6, 12, 18	2.75	Spherical
Taraghi et al.	7.11	20, 30, 40, 50, 60, 80	n/a	Hemispherical
Zainuddin et al.	n/a	40, 56	n/a	Hemispherical
Tita et al.	1.205	2.36, 5.91, 4.33, 10.82	1.8	Hemispherical
Abrate et al.	3.10, 6.81	2.31, 3.12, 4.61,6.25	n/a	Hemispherical
Hosseinzadeh et al.	2.5	30, 50, 100	2.4,, 2.8, 3, 4	Hemispherical
Sayer et al.	6.32	25-75	3.2, 3.9	Hemispherical

Pinnoji and Mahajan analyzed the damage caused by impact of a composite shell of a helmet. For this study, a drop test was used to drop a headform and helmet onto a flat surface. An accelerometer was placed at the center of the headform. From this drop, the acceleration time history was recorded in order to measure the peak head acceleration and to calculate the Head Injury Criterion (HIC). Impact velocities of 7.5 m/s and 9.0 m/s were used to validate the headform peak acceleration in comparison to a prior literature review. Several drops were completed at different points on the helmet. The peak acceleration at each point was recorded and analyzed. This study also looked at the damage mechanisms within the composite after impact [27].

Pinnoji and Mahajan compared an ABS helmet shell to a cross-ply composite shell. In comparison, the ABS shell showed a lower contact force compared to the composite shell. This is due to the composite shell having a greater stiffness compared to the ABS shell. Also, the ABS shell recorded a lower head peak acceleration compared to the composite shell, and therefore a lower HIC. Pinnoji and Mahajan concluded that composite shells do not absorb a significant amount of energy in order to reduce impact forces to the head when compared to a thermoplastic helmet shell [27].

Based upon a comprehensive literature review of the testing that has been completed on flat panel composite specimens, it was decided that a modified hollow, square specimen holder (similar to the one seen in Figure 6.2) would be used to stabilize the composites to be impacted. The reason for choosing this structure is because samples that were provided for testing were fabricated in 8” by 8” square panels. Also, this shape was chosen because it needed to fit within the constraints of the 9.5” by 9.5” square base of the Lansmont Cushion Tester used for dynamic drop weight impact testing. Modifications to the specimen holder included a cut-out section on the front of the box. This enabled an allowable area for the high speed camera to capture the displacement of the impact.

The impact energy that was decided upon for testing was 20 J. Previous literature impacted flat panel composite panels at an impact energy ranging from 1.5 to 120 J depending on the thickness of the samples used. Based upon the thickness of the composites provided for testing, an impact energy of 20 J seemed to be most representative of what had been done in literature. Finally, the choice to use a hemispherical impactor was decided upon based on the requirements of ASTM D7136-12 which specifies the testing conditions of performing drop weight impact events on flat panel polymer composites.

CHAPTER SEVEN

MATERIALS AND METHODS

The overall purpose of the complete study is to design, test, and fabricate a composite with superior energy absorption and dissipation properties (compared to the standard polycarbonate) for the use in the outer shell of the football helmet. This thesis focuses on the preliminary testing. The preliminary testing seeks to identify the top ten performers of the twenty-two different specimen configurations that demonstrated the best energy absorption with reasonable displacement under dynamic drop weight conditions. The down selection will be based on the initial results of preliminary testing, while refining the composition and structure of the composite specimens. Each of the following materials sections was critical in influencing the design and development of the testing methods used to achieve the overall goal of the study.

7.1. Flat Panel Fabrication

In this preliminary study, flat panel composite specimens underwent dynamic drop weight impact testing. Each configuration of composite specimen was made up of a combination of several different layers (plys) of fabrics. Fabrics used to make the flat panel composites were fabricated in several ways. Some fabrics contained yarns of a single material fiber (in one strand of yarn) woven together to make a single material fabric ply. Other fabrics contained hybrid yarns with multiple material fibers combined in one yarn and then woven together in a specific configuration to make up a fabric containing multiple fibers in a single yarn. Whereas other fabrics are hybrid weaves with several single material yarns (described above) all woven together to make a hybrid fabric. It was a combination of yarns, hybrid yarns, and hybrid weaves that were used to construct the combination of layers of the flat panel composite specimens. A variety of fibers were used to make the yarns and fabrics in the flat panel composite specimens including Innegra H, Innegra S, Kevlar, Aramid, basalt, S glass, E glass, and carbon.

The flat panel composite specimens used in this preliminary study were fabricated by Russ Emanis in his laboratory in Keller, Texas. The specimens were manufactured by means of a vacuum infusion process into 8” by 8” inch flat panel composite specimens. A detailed outline of the vacuum infusion process, including pictures, used by Emanis can be found in Appendix A.

7.2. Experimental Testing Apparatus

Dynamic drop weight impact testing was performed on flat panel composite specimens. The testing apparatus used to perform these tests is found in the Sonoco Transport Packaging Testing Laboratory at Clemson University. The testing apparatus used to perform dynamic drop weight impact testing was the Lansmont Cushion Tester, model 23. The system was set up to be in compliance with ASTM D-1596. Figure 7.1 shows the setup of the complete cushion drop testing system. A computer program was used to capture the data of each drop event. The data captured from the impact event was outputted in the program as a shock pulse curve. The program used was the Test Partner 3 (TP3) ETC Version 3.5.10 Software of Lansmont Corporation (Monterey, CA). For this study, the data taken from the TP3 software was the acceleration and duration of impact at a recording setup of 100 msec. Measurements are captured by a shock accelerometer, model # 353B15, serial # 135603 of PCB Piezotronics with an accuracy of ± 10% (spec sheet found in Appendix B). The impact velocity that the specimen experiences was captured by the Lansmont Test Partner Velocity Sensor® Version 2.0.1 of Lansmont Coporation: Monterey, CA; serial #: 0156, with a tested accuracy of 99.9% at 25 °C.

Figure 7.1 Setup of the Lansmont Cushion Tester in the Sonoco Transport Packaging Testing Laboratory.

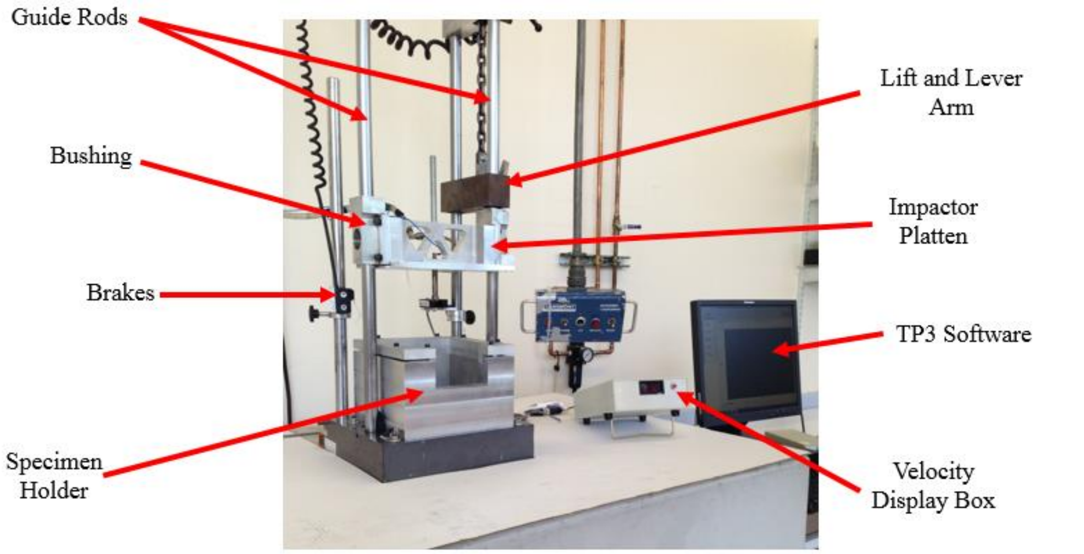


Figure 7.2 Set up of the Lansmont Cushion Tester with the TP3 Software used for data capture and analysis.

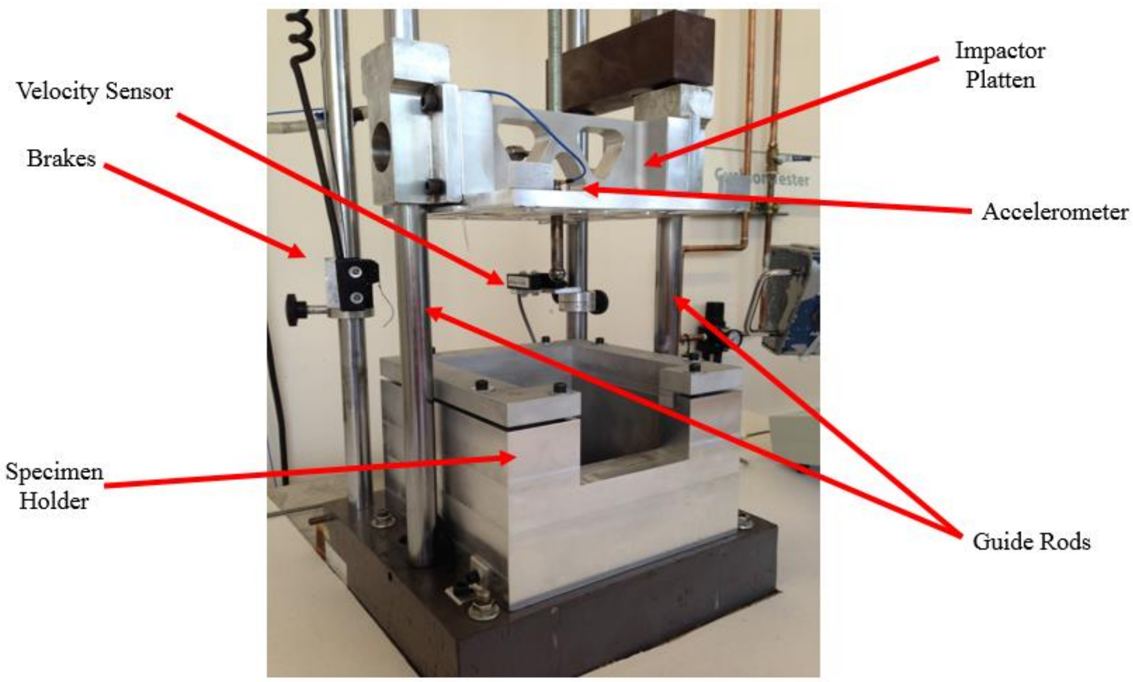


Figure 7.3 A close-up of the impactor platen and specimen holder.

The Cushion Testing System contains two guide rods (Figure 7.2) in which a platen can move freely up and down. The movement of the platten is guided by a lift, attached to the right guide rod, which contains a lever arm. The lever arm hooks to the right bushing holding the platen. When the lift is triggered at the appropriate drop height, the lever arm releases the platen, and the platen drops in free fall to impact the sample. During the free fall event, there is some friction present between the guide rods and bushings. This means that the actual drop height of the platen is greater than the equivalent free fall drop height. To help decrease the friction, Chevron Way Oil Vistac ISO 63, product of Lansmont Corporation, is used to grease the guide rods before performing drop tests.

The Cushion Tester is equipped with a brake system (see Figure 7.4). The brake switch is produced by Honeywell S&C, part number: 23F4149. The brake switch contains a lever arm that is strategically bent. When the lever arm contacts the platen, the brake system is triggered. The brakes are positioned so that the lever arm contacts the platen at the exact point when the impactor tip touches the loaded specimen. The brake system is run by an air compression system that is connected to the bushings attached to the guide rods. At the point that the brakes are triggered, air is released into the bushings of the Cushion Tester to catch the platen after impact.

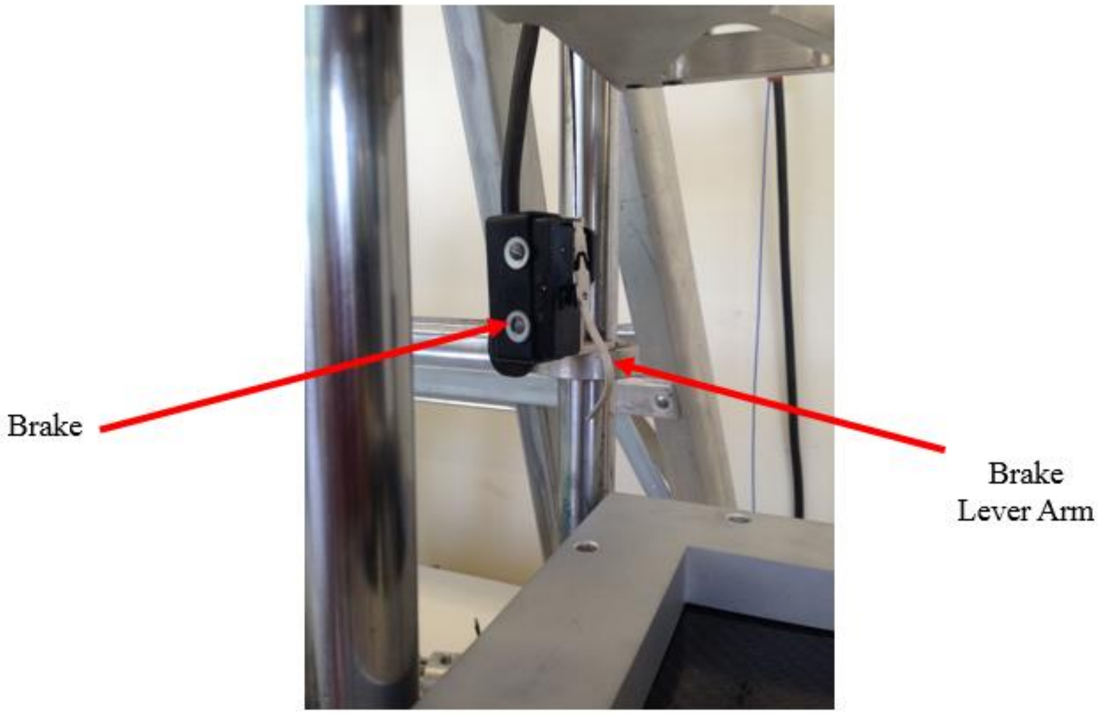


Figure 7.4 Brake system used on the Cushion Tester.

The impactor platen on the Cushion Tester was fabricated by Dustin Gravley of Clemson University's Machine and Technical Services. The impactor base and tip were made of Grade A2 Tool Steel. The impactor tip was made to be in compliance with ASTM D7136-12, and therefore, the tip diameter was 16 ± 0.1 mm (0.625 ± 0.005 in), and the tip was heat treated to obtain a hardness of 60-62 HRC [66].

Figure 7.5 Tip of the impactor made in compliance with ASTM D7136-12.

The base of the impactor contains numerous cut-out holes in order to decrease the weight of the platen. This ensures that the operator can more freely manipulate the weight of the impactor to desired preferences based upon the necessary drop height and impact energy. The total weight of the impactor was 4.12 kg. However, 5 lbs was added to make the overall weight 6.445 kg. By adding weight to the impactor, this allowed the drop height to lower significantly. With the Cushion Testin System, the lower the drop height, the less effect friction has on the free fall event. As drop height is increased, the effect of friction increases. The impactor platen was equipped with a shock accelerometer, model number 353B15, produced by PCB Piezotronics. This accelerometer measures the acceleration that the sample experiences upon impact. Figure 7.6 shows a close-up view of the impactor platen.

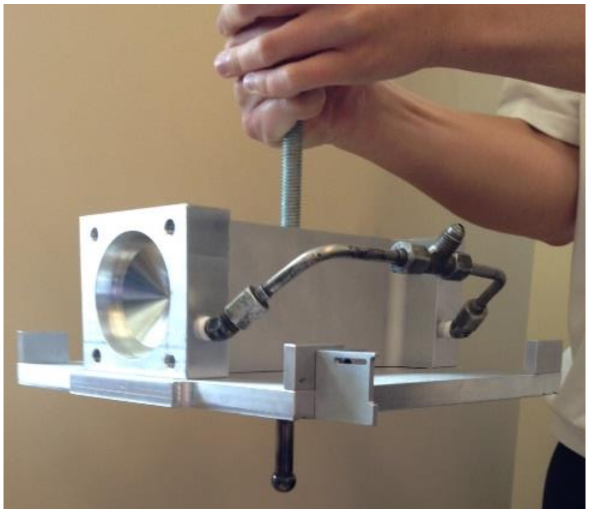


Figure 7.6 Impactor platten used to perform dynamic drop weight impact tests on the Cushion Tester.

7.3. Specimen Holder

The 8” by 8” flat panel composite specimens were fixed in the specimen holder for impact events. The specimen holder was fabricated by Dustin Gravley of Clemson University’s Machine and Technical Services. It is made of Aluminum 6061T based on a review of prior literature’s use of aluminum for specimen holders for dynamic drop weight impact events of composite specimens. There are four separate pieces that make up the specimen holder. These pieces include the base, cover, shim, and screws. Table 7.1 gives the dimensions of each separate piece. The total weight of the specimen holder is 26.95 lb.

Table 7.1 Dimensions of the parts that make up the specimen holder.

Part	Mass [kg]	Weight [N]
Base	10.52	103.2
Cover	1.361	13.34
Shim	0.2585	2.535
Screws	0.0680	0.6672

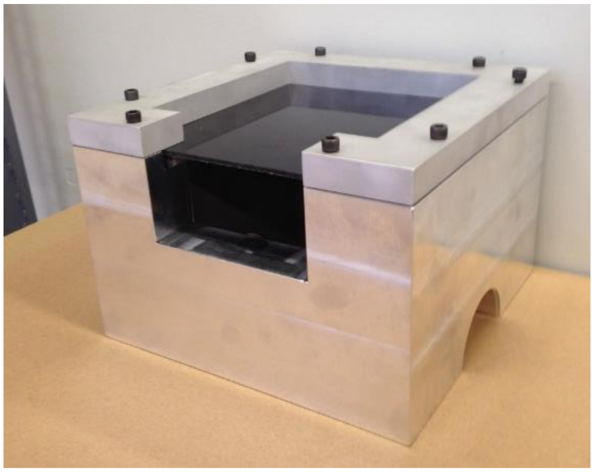


Figure 7.7 The complete specimen holder with a polycarbonate sample loaded.

The specimen holder is a hollow square box with dimensions of 9.5” by 9.5”. The height of the specimen holder is 5.75”. The specimen holder contains an opening in the front to allow the high speed video of the deforming event to be captured upon impact (Figure 7.8). This opening is centered in the front of the box. The dimensions of the opening are 2.25” deep from the top of the base and 4.50” wide.

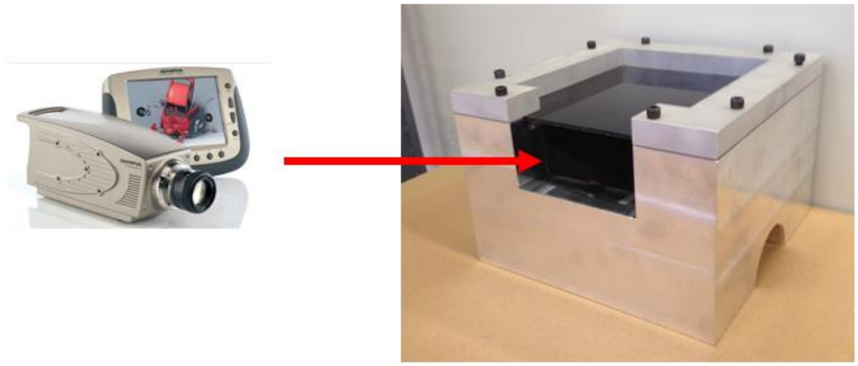


Figure 7.8

On both lateral sides of the specimen holder, there is a hemispherical opening that is 3.00” in diameter. The purpose of these openings is to allow for extra light to enter inside the box. Figure 7.9 shows the specimen holder labelled with the corresponding dimensions.

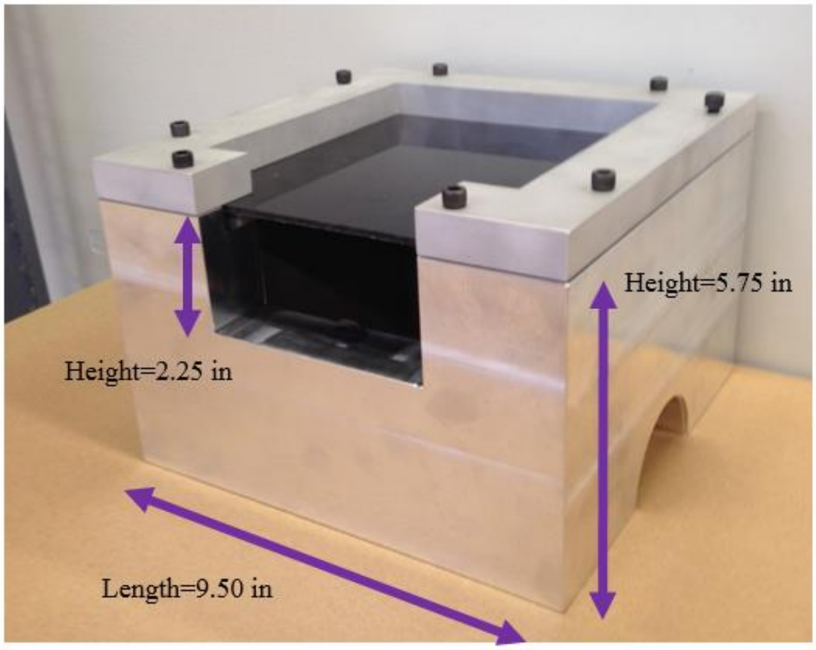


Figure 7.9 Specimen holder with dimensions labelled.

One key feature of the specimen holder is that it contains an internal lip that allows the 8” by 8” flat panel specimens to fit loosely within the base. A shim is placed on the ledge of the internal lip, and the flat panel is placed on top of the shim. The cover is then placed on top of the flat panel composite, and the eight screws are inserted and uniformly tightened to a torque of 40 in-lb.

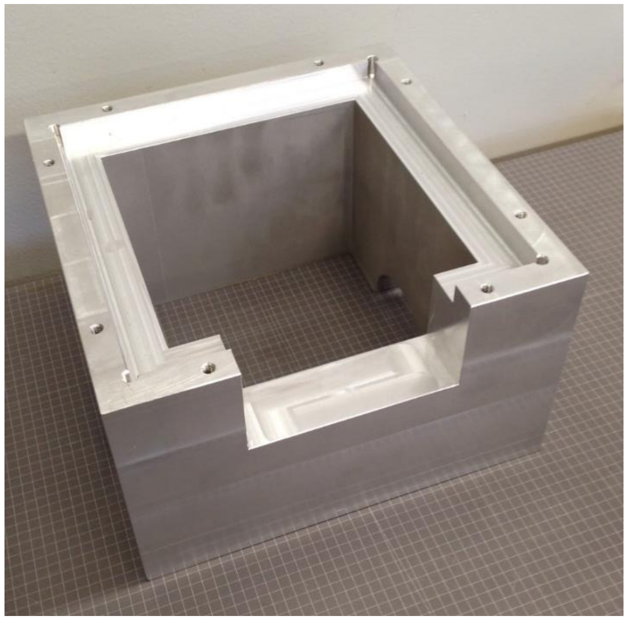


Figure 7.10 Specimen holder without the cover to show the internal lip that the flat panel composite rests on.

7.4. High Speed Camera Overview

In order to capture the drop weight impact event, a high speed camera was used. The high speed camera used in this project to capture the impact velocity, rebound velocity, and the displacement of the specimen upon impact was the i-Speed 3 T2 8 GB Color Camera, serial # 1100127 from Olympus of Center Valley, PA (Figure 7.11). During testing, a 105 mm lens was used to capture the high speed video at 2,000 fps. Key features of the camera are listen in Table 7.2.

Figure 7.11 Olympus i-Speed 3 Color Camera with the controller display unit (CDU).

Table 7.2 Specifications of the Olympus i-Speed 3 Color Camera.

Features	
Resolution	1280 x 1024 @ 2,000 fps
Maximum Frame Rate	150,000 fps
Record Time	2.4 seconds

High Speed Camera Set-up

After the sample was loaded, the high speed camera and appropriate lighting were positioned in front of the specimen holder box and cushion tester. The camera was positioned to be 57.0” from the ground and placed 44.8” away from the specimen holder. The proper positioning of the camera and lighting allowed an appropriate view of the impact event to be captured on the high speed camera. The area displayed on the CPU was 11.63” by 8.13” giving a resolution of 94.6 inches^2/1280 x 1024. Figure 7.12 shows the arrangement of the high speed camera and lighting in front of the cushion tester, and Figure 7.13 shows a close up of the camera and lighting.

Figure 7.12

Figure 7.13

The high speed camera was set to all the appropriate specifications and calibrations in order to capture the best image of the impact event. The camera was set to a high sensitivity due to the available lighting. A capture rate of 2,000 frames per second (fps) was programmed, and the trigger mode was set to be a video falling event. This means that the camera will start recording once a falling event occurs within the view of the lens. In order to set the trigger mode, a desired area distinguished on CPU screen was set. Once the impactor tip entered the plane of this area, the camera recording began triggering. The location selected to start the trigger event was the horizontal plane just above the velocity sensor. Finally, calibration of the camera was done by programming the measurement of the diameter of the impactor tip (0.625”).

Once the calibrations and specifications were set, the i-Focus feature of the high speed camera was utilized to aid in focusing the lens on the desired area. The focus point was the impactor tip because this was the point at where the measurements would be taken.

7.5. Dynamic Drop Weight Impact Testing Protocol

Cushion Tester System Set-up

Using the materials and testing equipment that were just described, the development of testing methods for preliminary testing were developed in collaboration with the industry collaborators involved in the study. Once the goals of the study were decided upon, the design of testing protocols and preliminary testing on flat panel composite specimens began. For each of the twenty-two different composite configurations, there was a sample size of six. Each of the six flat panels underwent a single dynamic drop weight impact event. A high speed video was taken and data from the TP3 software were recorded for each flat panel impact event. Figure 7.14 shows a typical cushion curve output by the TP3 software. Six of each baseline football helmet shell materials, ABS and PC, also underwent a single dynamic drop weight impact event.

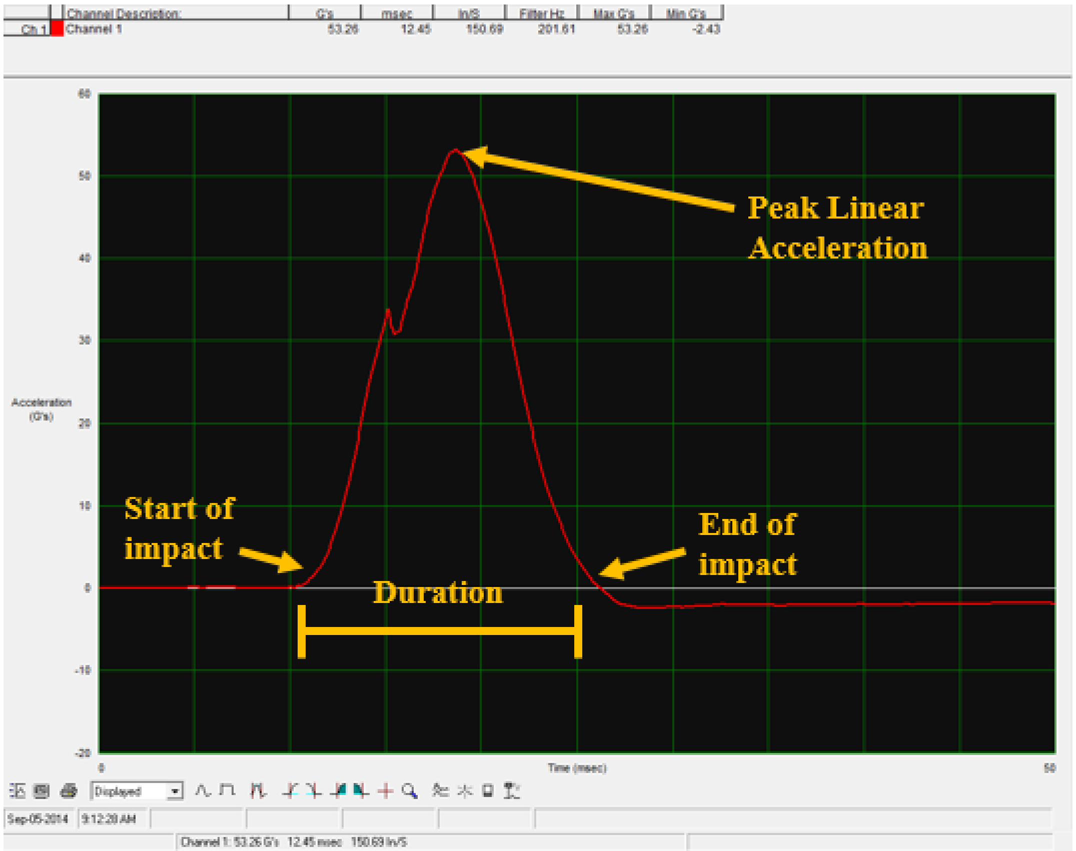


Figure 7.14 Representation of an impact event shock pulse curve from the TP3 software.

The primary goal of the preliminary testing was to down-select ten different flat panel composite specimen configurations from the original twenty-two configurations. In order to down-select, dynamic drop weight impact testing needed to be performed on the flat panel composite specimens and the performance of each configuration needed to be evaluated.

Based on a literature review of impact testing on flat panel composites, the industry collaborators decided that the initial twenty-two configurations would all be impacted at 20 J of kinetic energy. In order to achieve an impact kinetic energy of 20 J, the impact velocity needed to be calculated. For the dynamic drop weight impact event, kinetic energy will be transferred into potential energy upon impact. Therefore, the impact velocity was found using the kinetic energy equation (Equation 7.1):

Equation 7.1 $$v_i = \sqrt{\frac{2(KE)}{m}}$$

where v_i is the impact velocity [m/s], KE is the kinetic energy (20 J), and m is the mass of the impactor (6.445 kg). These requirements gave an impact velocity of 2.49 m/s. Due to the fact that there is friction in the guide rods during free fall, the equivalent drop height needed to be calculated. In order to find the equivalent drop height, Equation 7.2 was used. This equation takes into account the amount of energy lost due to friction in free fall.

Equation 7.2 $$h_{eq} = \frac{V_i^2}{2g}$$

where h_{eq} is the equivalent free fall drop height [m], v_i is the impact velocity [m/s], and g is the gravity constant [m/s^2]. Using Equation 7.2 and the calculated impact velocity of 2.49 m/s, the equivalent free fall height was calculated to be 0.316 m (12.44 inches).

With the Cushion Tester System used, there was a substantial amount of friction during free fall. To account for this, the drop height needed to be raised to a higher point in order to achieve the calculated impact velocity. Through trial and error of performing drop tests on extra samples, the appropriate drop height to achieve 20 J of impact energy was found to be roughly 0.432 m (17 inches) depending on the thickness of the loaded sample.

Once the Cushion Tester lift was raised to the appropriate drop height, the flat panel specimen was loaded into the specimen holder. The top of the specimen was positioned on the backside of the specimen holder (closest to wall). The directions that each specimen was loaded into the holder were kept consistent throughout testing. Each sample was centered in the specimen holder before the cover and screws were put on. The eight screws used to secure the cover of the specimen holder were all tightened to a torque of 40 in-lb using a torque wrench. Keeping the torque consistent around the fixed specimen ensured that there was an even distribution of pressure applied to the sample as it was secured. Once the sample was loaded into the specimen holder, the brakes and velocity sensor were realigned and set.

Impact Event

With the high speed camera set-up and the flat panel specimen loaded, the dynamic drop weight impact event was ready to occur. The platten was raised with the lift and lever arm to the pre-set drop height. At this height, the lever arm released the platen, and the impactor platen fell in free fall to impact the fixed specimen. Throughout the impact event, the TP3 software captured the acceleration, duration of impact, and filter frequency used to smooth the shock pulse curve. The velocity sensor displayed the exact impact velocity with which the impactor contacted the specimen. Finally, the high speed camera recorded the impact event at 2,000 fps. The video captured was analyzed on the CPU.

Recording of the impact event on the high speed camera allowed for researchers to return to the video of the event to get data point measurements. Measurements that were taken were the impact velocity, rebound velocity, and displacement of the specimen upon impact. In order to better follow the indenter during the impact event, a marker was positioned on the stem of the impactor tip. Each measurement was taken by watching the video at the point of interest at 1 fps.

In order to find the impact velocity, the frame immediately before impact was found. On the CPU, this dot was marked as the "set point" (see Figure 7.15).

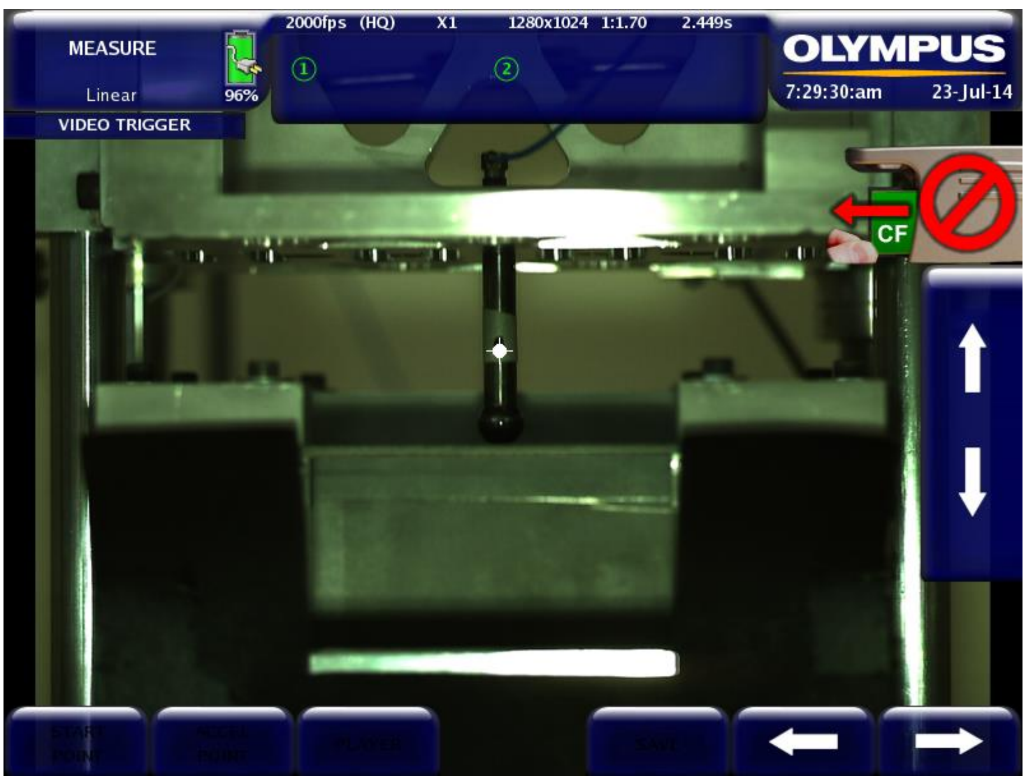


Figure 7.15 Data capture of the frame directly before the impactor tip contacts the composite in order to capture impact velocity.

To keep measurements consistent, video was rewound 20 frames from the set point frame directly before impact. At the frame 20 frames from the set point, the marker on the stem was followed and marked again. The distance between the two markers over the time that the camera captured the video was used to calculate the impact velocity (Figure 7.16).

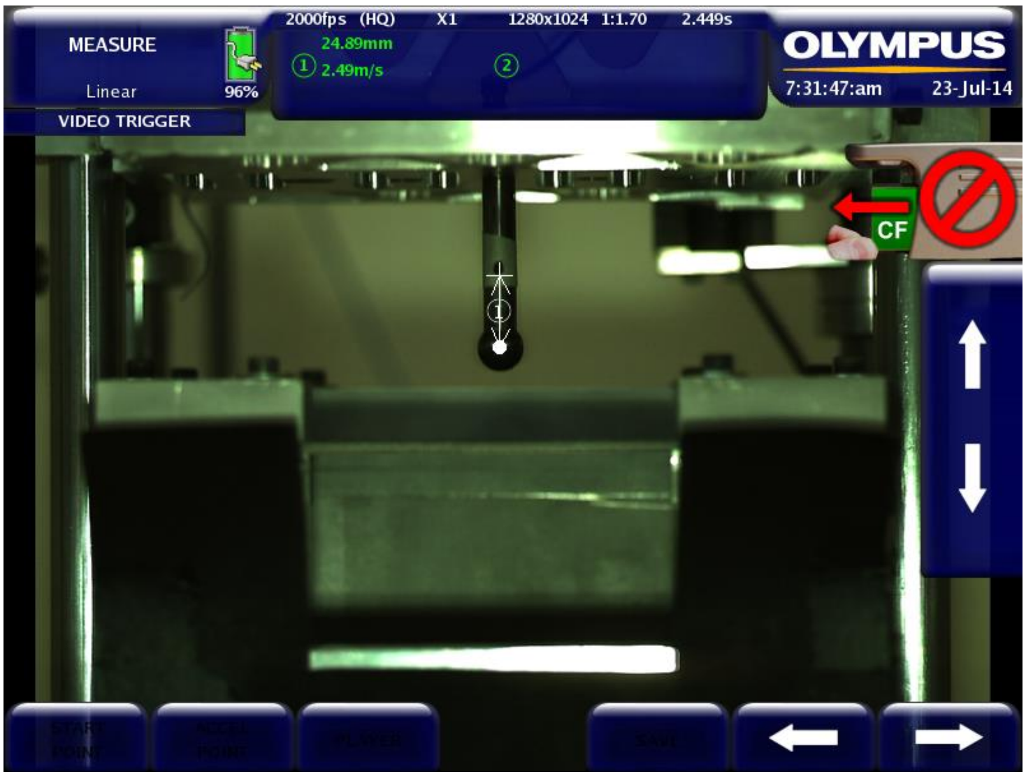


Figure 7.16 Data capture 20 frames prior to the frame directly before impact in order to capture the impact velocity.

A similar method was used to find the rebound velocity. At the frame immediately after the indenter tip leaves the specimen, the marker on the stem of the impactor tip is marked as the “set point” (see Figure 7.17)

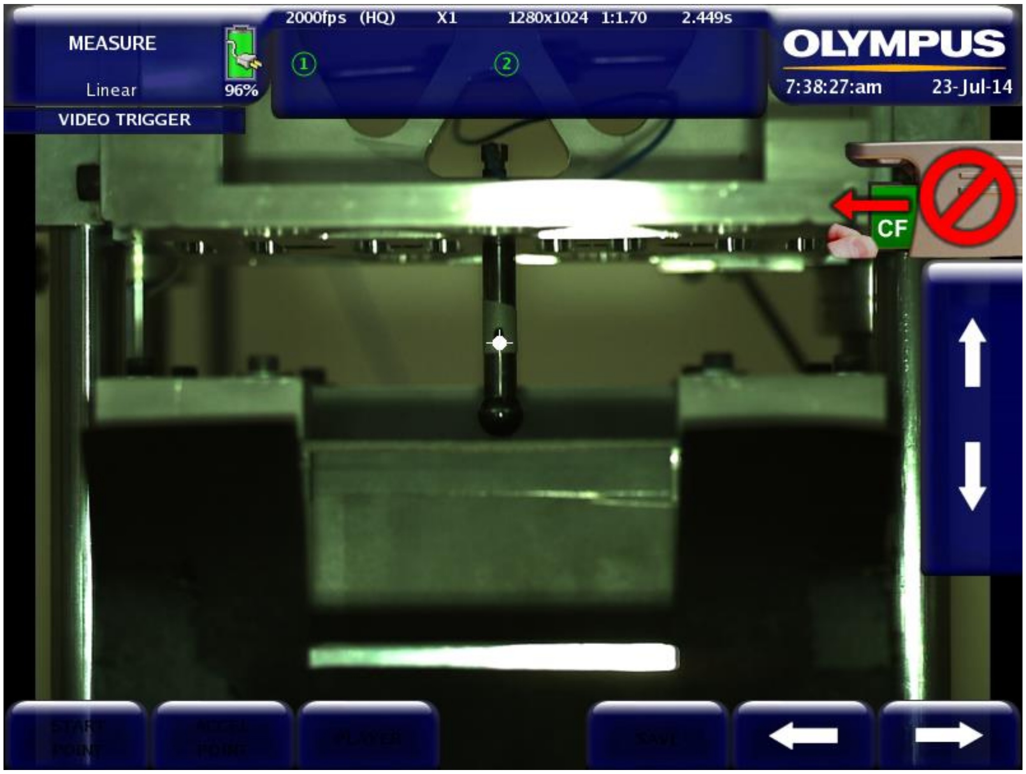


Figure 7.17 Data capture of the frame directly after the impactor tip leaves contacts the composite in order to capture rebound velocity.

Again, to keep measurements consistent, the camera was fast-forwarded 20 frames from the point that the impactor tip leaves the specimen. The marker on the stem was followed and marked a second time. The distance between the two markers over the time that the camera captured the video was used to calculate the rebound velocity (see Figure 7.18).

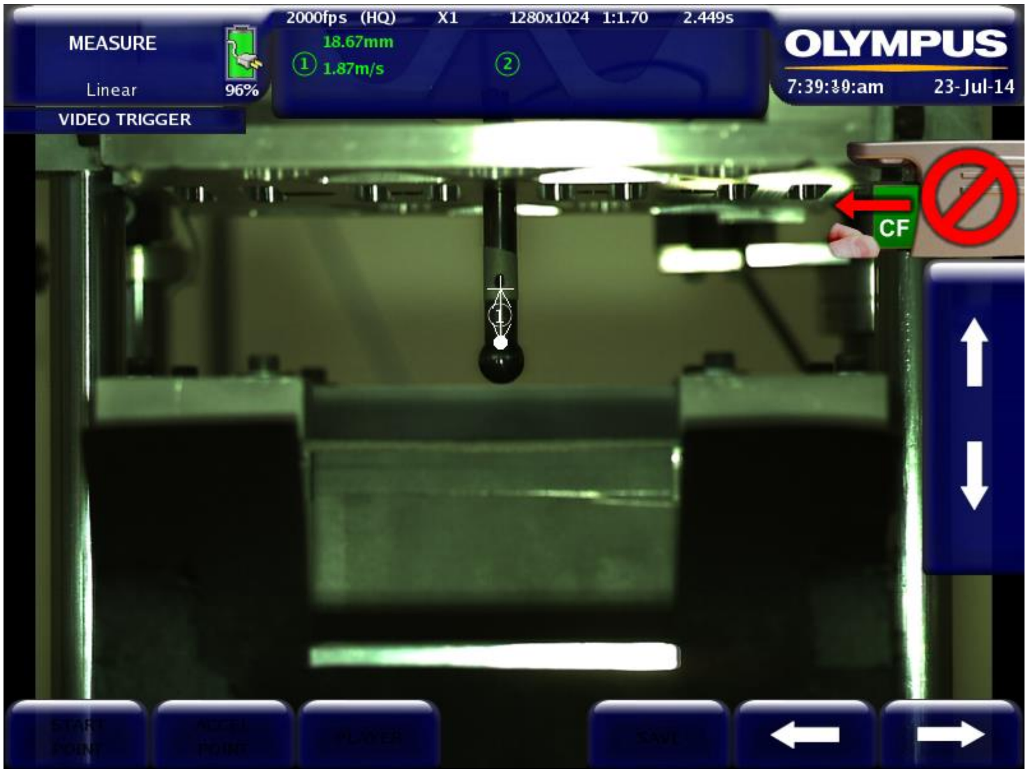


Figure 7.18 Data capture 20 frames after the frame when the impactor tips leaves contact with the composite in order to capture rebound velocity.

The displacement was found by following the marker on the stem of the impactor. At the lowest point of movement, the marker was labelled as the "set point" (see Figure 7.19).

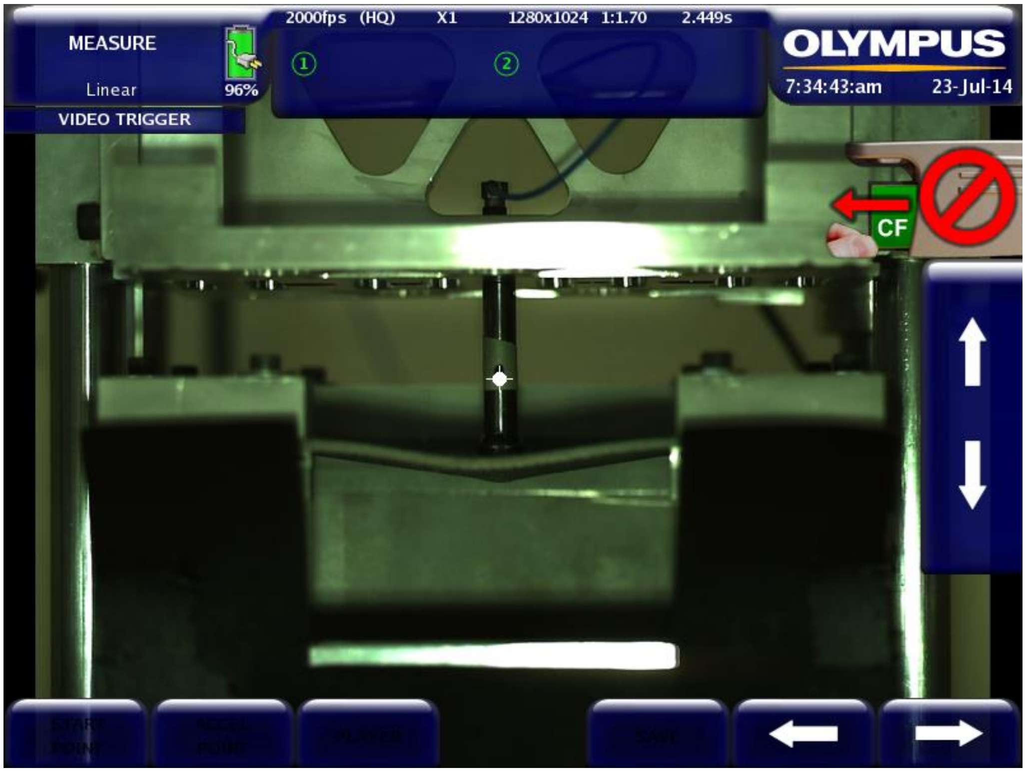


Figure 7.19 "Set point" placed on the marker at the lowest point of impact.

The video was rewound to the frame directly before impact, and a second dot was placed on the marker at the initial impact point. The distance between these two points was recorded (Figure 7.20).

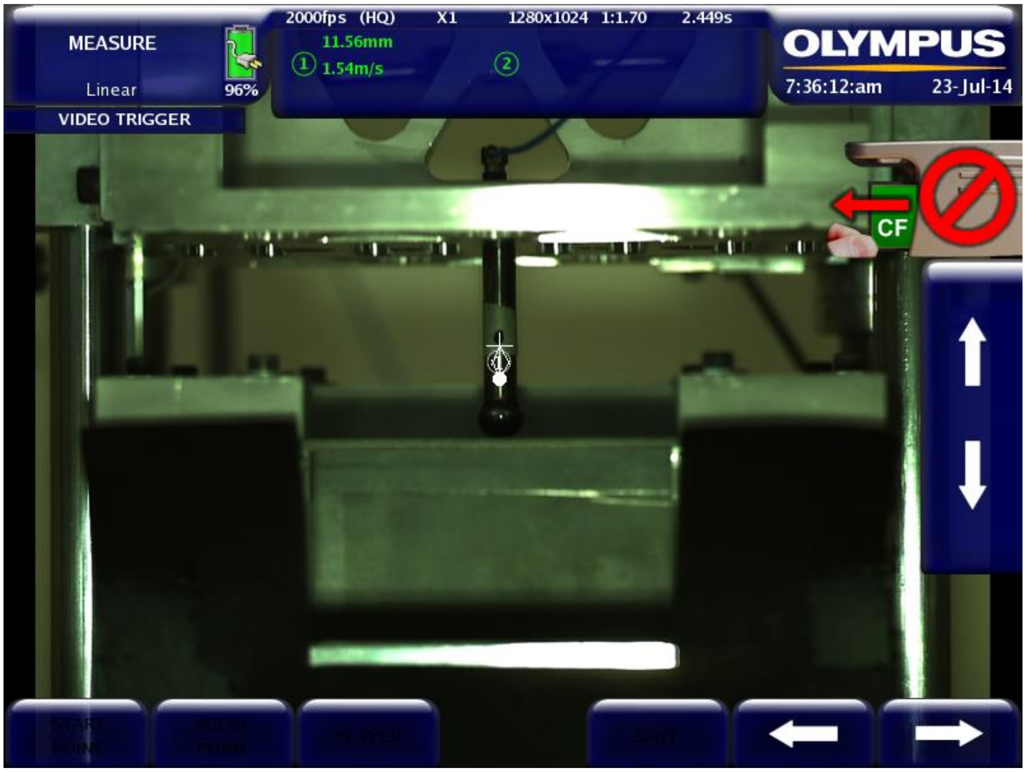


Figure 7.20 Second dot placed on the marker at the initial point of impact in order to capture the displacement of the composite.

CHAPTER EIGHT

RESULTS

8.1. Material Characteristics

The first aim of the study was to fabricate a composite material with a density that was equal to or less than that of polycarbonate. In order to evaluate the first aim, length, width, and height measurements were taken in order to calculate the density of each composite configuration. The mass of each flat panel composite was recorded. Based upon the measurements, a graph comparing the composite densities to polycarbonate was constructed. The density of polycarbonate was 1178.4 kg/m^3. It can be seen from Figure 8.1 that seventeen of the twenty-two constructed composites have a density that is less than that of polycarbonate (not including ABS). The remaining six composites all have densities that are slightly higher than that of polycarbonate. ABS is material used in the outer shell of some youth football helmets, but it is not used in higher levels of play. This material was tested to see how its properties and impact performance are comparable to that of polycarbonate.

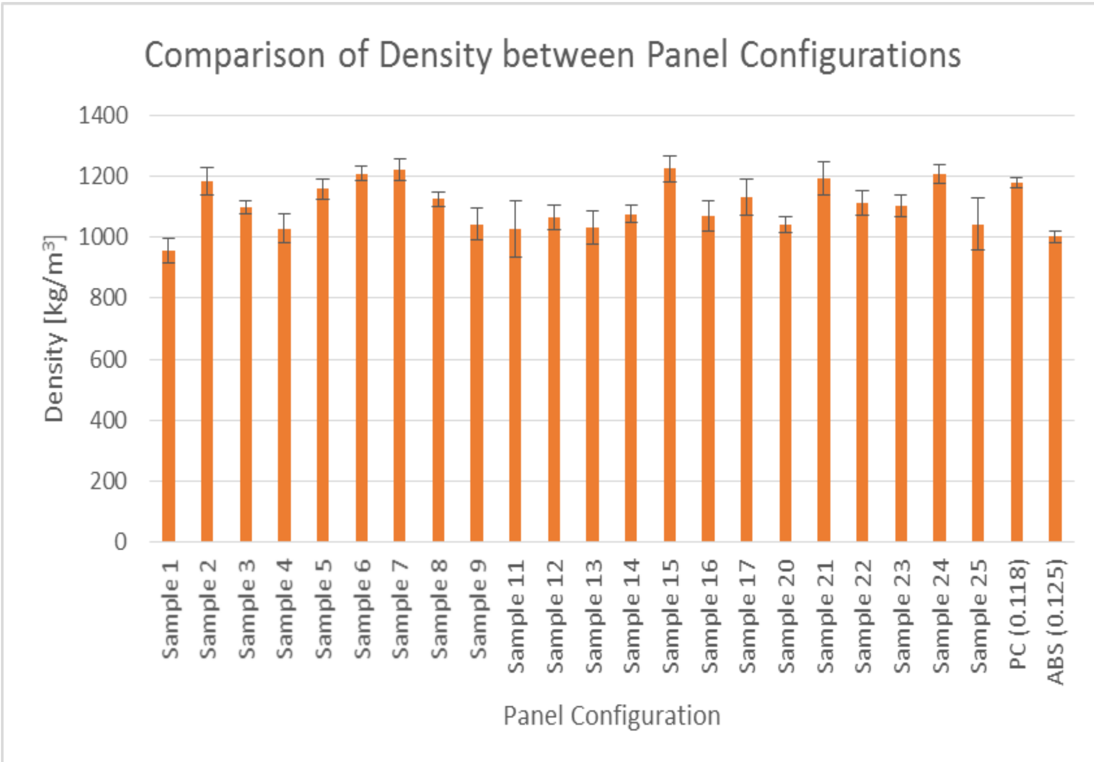


Figure 8.1 Comparison of the density of the composite specimens to the standard polycarbonate material.

8.2. Dynamic Drop Weight Impact Testing

The first part of the third aim for Phase I of the complete study sought to determine which of the composites will absorb a greater amount of energy compared to the standard polycarbonate material currently used in the outer shell of the football helmet. This was evaluated through monitoring the impact and rebound velocities occurring throughout the dynamic drop weight impact event in order to calculate the change in kinetic energy. The second part of the third aim for Phase I sought to determine which of the composites will displace an amount that is equal to or less than the standard polycarbonate material. This was evaluated using a recorded image of the impact event and obtaining dimensions of the movement of the composite during the impact event with the CPU of the high speed camera.

To analyze the change in kinetic energy and displacement endured by the samples, flat panel composites underwent dynamic drop weight impact events. Figure 8.2 shows the change in kinetic energy between composites compared to polycarbonate. The change in kinetic energy is defined as the kinetic energy upon impact (calculated from the impact velocity) minus the change in kinetic energy at rebound (calculated from the rebound velocity). During impact testing, polycarbonate underwent a change in kinetic energy of 11.9 J. From the testing of the composites, there were seven composites that experienced a greater amount of change in kinetic energy compared to composites. There were six composites that experienced a lesser amount of change in kinetic energy, but it was still comparable to the change in kinetic energy experienced by polycarbonate. This change in kinetic energy cannot completely be attributed to complete absorption of energy by the composite structure. Although most energy was absorbed by the composite, some energy is lost to other forms of energy as well as through visible destructive mechanisms. It must be noted that ABS, which is the material used in the outer shell of youth football helmets, has the greatest change in kinetic energy. However, during impact testing, all samples of ABS tested cracked upon impact, so there was energy lost due to destruction of the sample. Overall, composites did not have as drastic as fractures as ABS demonstrated. Additional graphs comparing the normalized change in kinetic energy based upon density can be found in Appendix C.

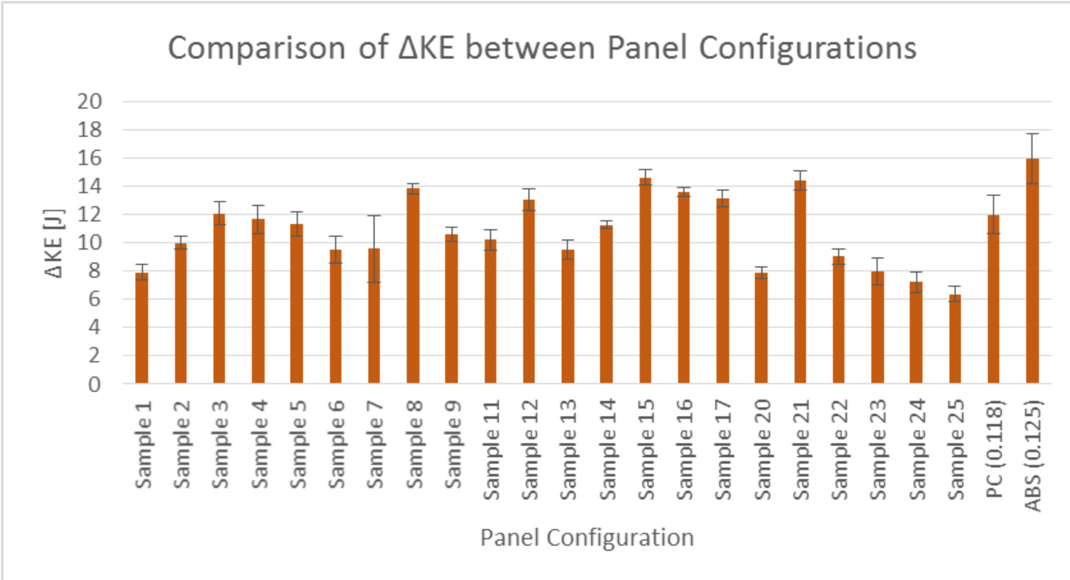


Figure 8.2 Comparison of the change in kinetic energy experienced by the composites, polycarbonate, and ABS from an impact event.

The comparison of the displacements experienced by the composites during the impact event can be seen in Figure 8.3. Due to measurement error while testing the first four composite sets, the displacements displayed in Figure 8.3 are the modified displacements. Modified displacement measurements were taken by measuring the displacement from the top of the composite at the point of impact to the bottom of the composite at the lowest point. Accurate displacements were measured correctly for the remaining nineteen samples. The modified verse accurate displacements are directly correlated, but the values for modified displacement are slightly higher due to the altered use of measurement to obtain the data. However, for the purpose of a consistent comparison, the modified displacements will be used. Figure 8.3 shows that all of the composite specimens, excluding ABS, displace less than polycarbonate. To further break the displacement data down, there were six composites (Samples 2, 3, 20, 21, 23, and 25) that displaced less than 15 mm when subject to 20 J of impact energy; there were fifteen composites (Samples 1, 4, 5, 6, 7, 8, 9, 11, 12, 13, 14, 16, 17, 22, and 24) that displaced between the range of 15 mm to 20 mm; and finally, Sample 15, was the only sample to displace more than 20 mm.

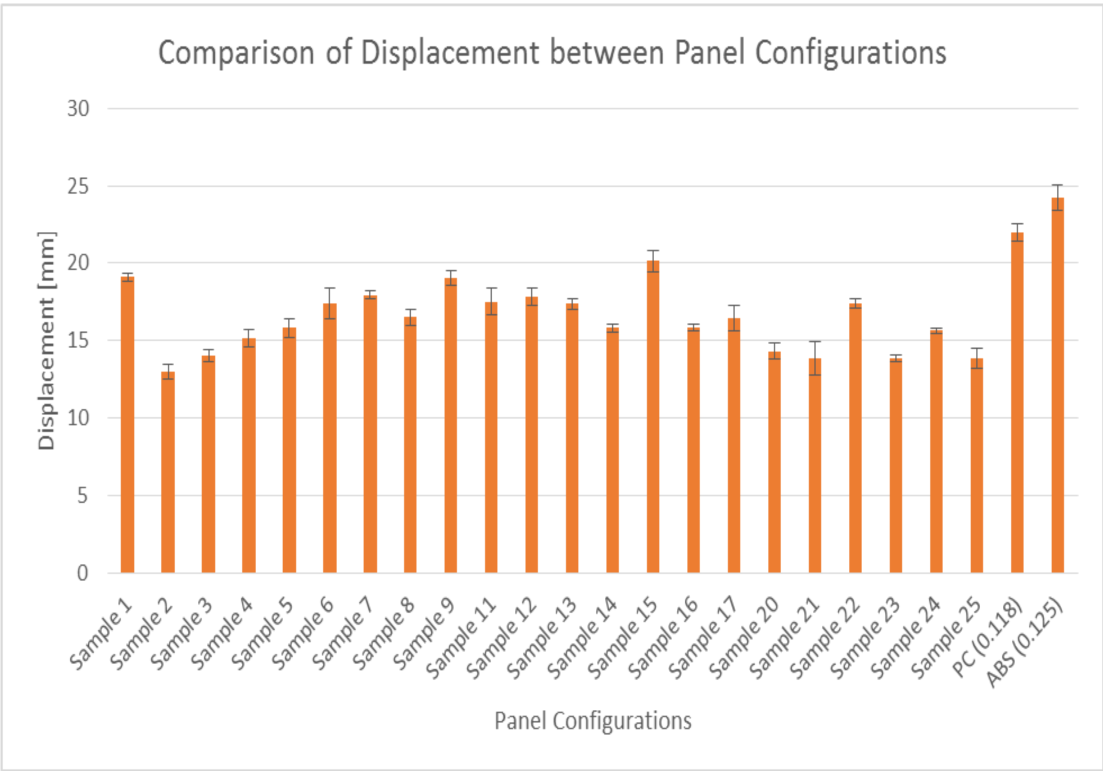


Figure 8.3 Comparison of the displacement experienced by the composites, polycarbonate, and ABS from an impact event.

For future testing and to aid in the data analysis of the complete study, Figure 8.4 and Figure 8. 5 were constructed to compare the acceleration that the composites experienced during impact as well as the duration that the impactor tip was in contact with the composite. Additional graphs used to aid in the understanding of impact responses between composites can be found in Appendix C. The acceleration experienced by polycarbonate at 20 J of impact energy was 45.2 G. In comparison, the acceleration experienced by the composites at 20 J of impact energy ranged from 46.2 G (Sample 15) to 78.3 G (Sample 25). The duration of contact at impact for polycarbonate was 15.5 msec. In comparison, the duration of contact for the composite specimens ranged from 9.75 msec (Sample 25) to 14.0 (Sample 15).

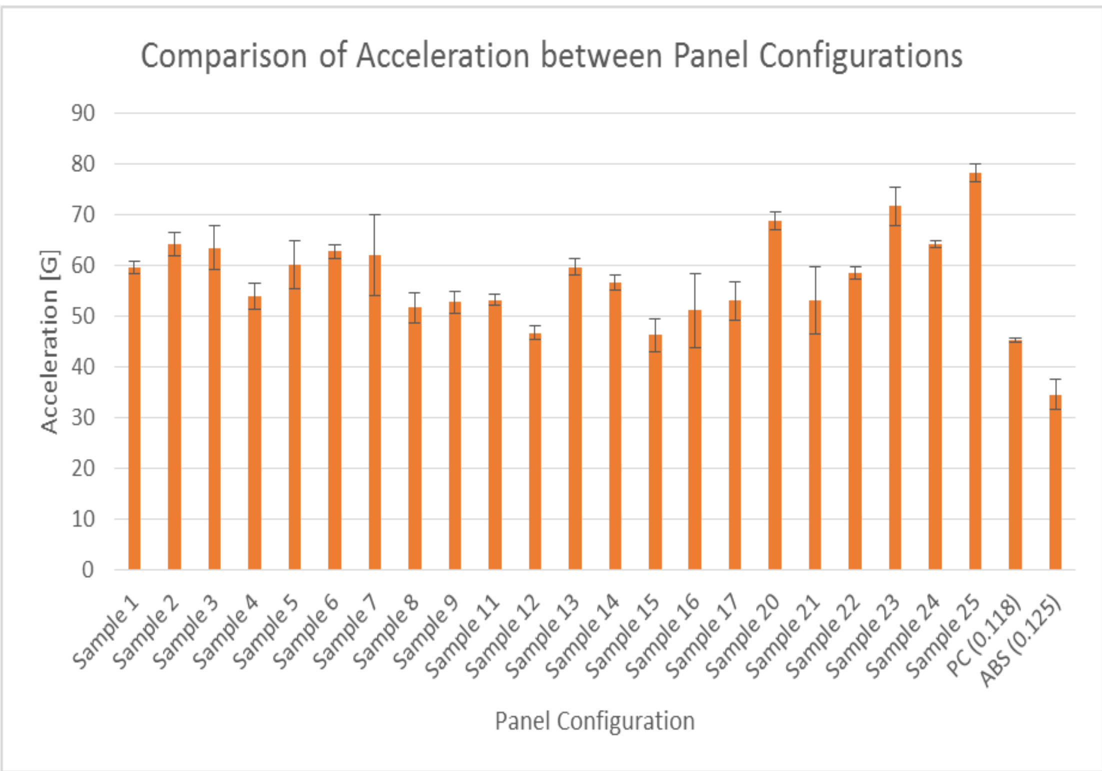


Figure 8.4 Comparison of the acceleration experienced by the composites, polycarbonate, and ABS from an impact event.

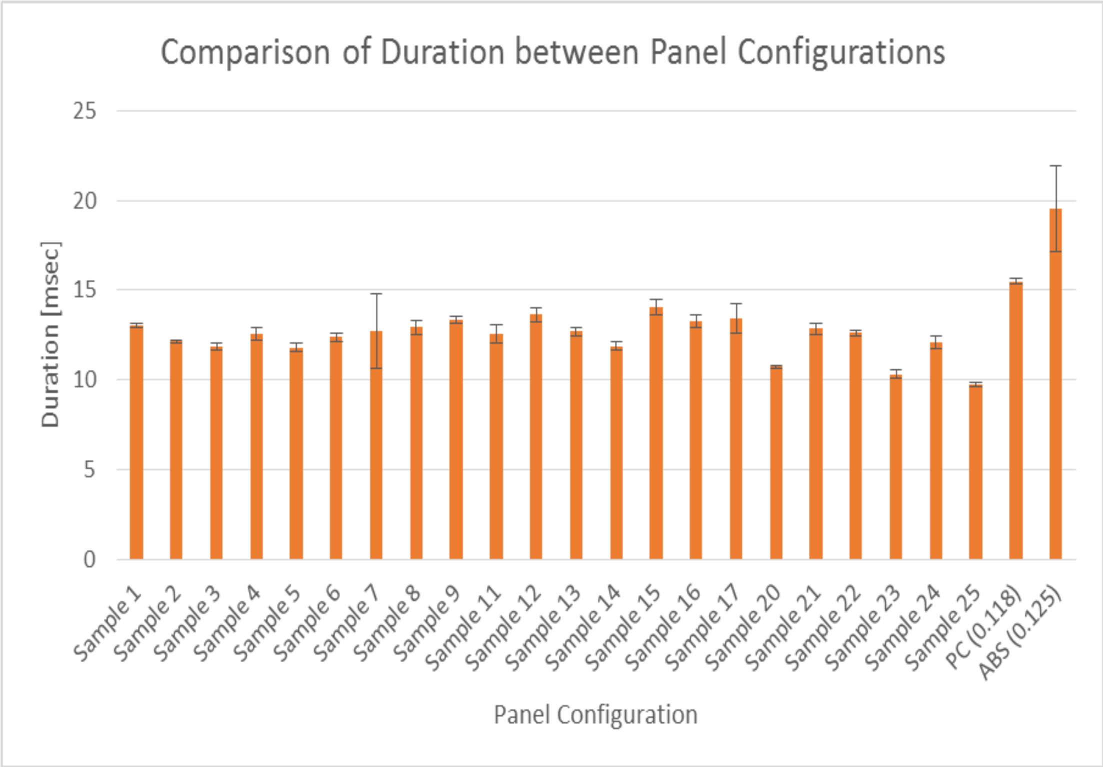


Figure 8.5 Comparison of the duration of contact experienced by the composites, polycarbonate, and ABS from an impact event.

In order to better understand the relationship between the first and second aims, Figure 8.6 shows a plot of the composites change in kinetic energy compared to density. The aim was to have a greater change in kinetic energy while having a density less than the standard polycarbonate. From Figure 8.6, the samples represented on the graph to the left of the polycarbonate marker (labelled with the red arrow) represent those composites with a density less than polycarbonate. All the markers above the polycarbonate arrow, represent the composites with a greater change in kinetic energy than polycarbonate. Therefore, markers to the left and above of the polycarbonate marker are key composites to evaluate the impact response. However, other factors must be taken into account, such as assessing the visible damage on the composites after subject to impact.

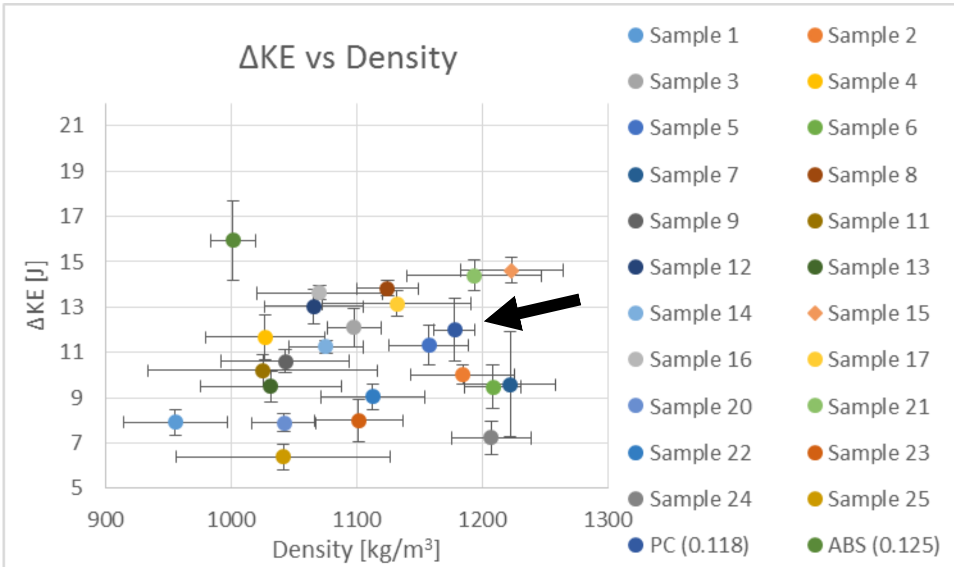


Figure 8.6 Sample representation comparison relation the change in kinetic energy to density.

A key aspect of Phase I was not only to find the top ten composite performers, but to also understand the response of the composites based upon the raw materials and hybrid yarn (commingled)/hybrid weave (co-woven) that the composite was constructed of. Figues 8.7-8.12 look at the response of the change in kinetic energy comparing the panels that were specifically designed and constructed to allow comparison between either raw materials or the type of hybrid composite used (commingled verse co-woven). It is important that the change in kinetic energy experienced by the composites not be the only method of evaluation. Visual inspection methods to evaluate the external damage were also used in combination with the data.

Figures 8.7-8.12 were all analyzed using a pooled t-test with 95% confidence, and the hypothesis that $\mu_a \neq \mu_b$. Figure 8.7 shows a representation of the response of several materials (E-glass, carbon, and basalt) in co-woven verse commingled composites. It can be seen that both E-glass and carbon experience a greater change in kinetic energy when co-woven ($p=0.1599$ and $p<0.0001$, respectively), although carbon experiences a statistically significant greater change in kinetic energy when co-woven compared to E-glass. Basalt's performance in both co-woven and commingled composites are comparable; however, basalt absorbs slightly more kinetic energy in a commingled composite ($p=0.3107$).

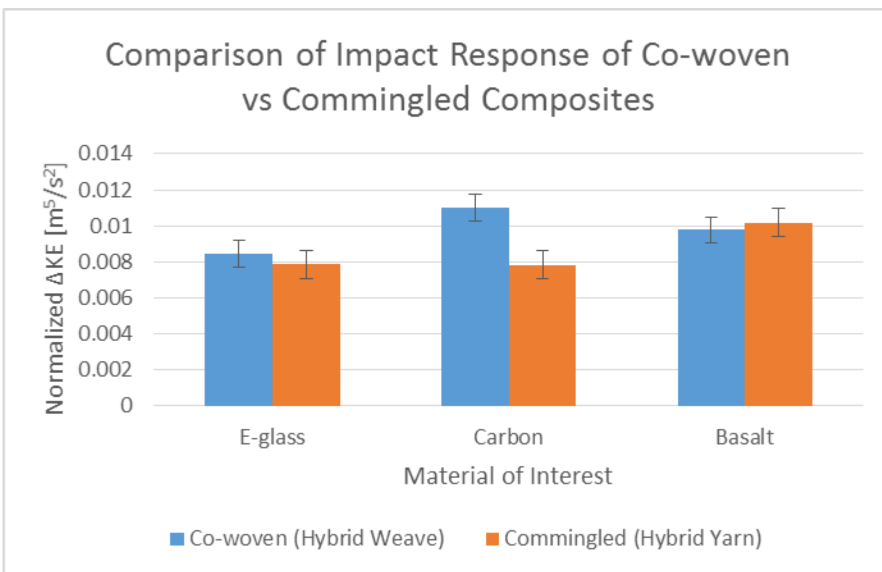


Figure 8.7 Comparison of the change in kinetic energy (normalized by density) between E-glass, carbon, and basalt hybrid weaves and hybrid yarns.

Figure 8.8 compares the response of tri-mingled hybrid yarns containing Innegra/Kevlar/Basalt and Innegra/Kevlar/Carbon. Under 20 J of impact energy, the tri-mingled hybrid yarn containing Innegra/Kevlar/Carbon experience a greater change in kinetic energy compared to the Innegra/Kevlar/Basalt tri-mingled hybrid yarn used in the composite configuration (p=0.0019), and these differences are statistically significant. Comparing the duration and acceleration of these two materials, the composite containing the basalt experienced 53.1 G of acceleration for 12.6 msec, whereas the composite containing the carbon experienced 46.6 G of acceleration for 13.6 msec.

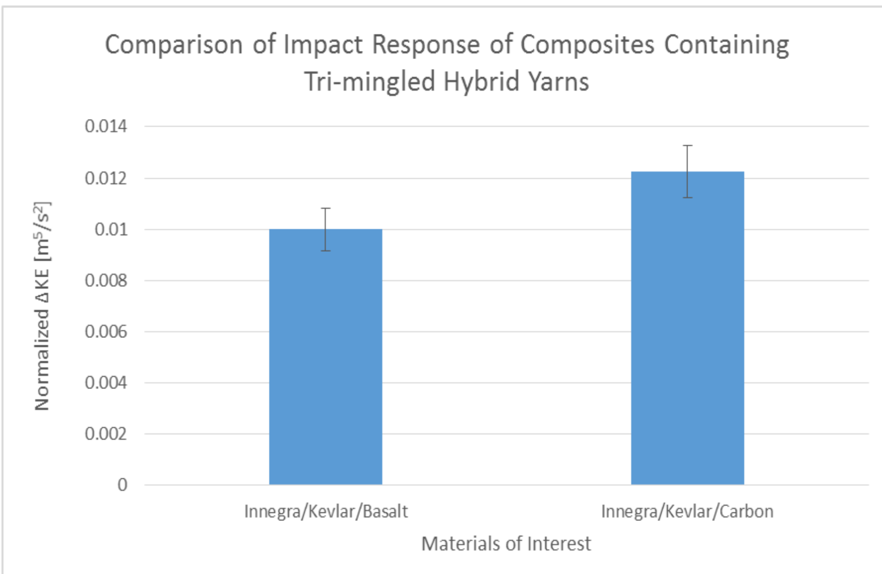


Figure 8.8 Comparison of the change in kinetic energy (normalized by density) between basalt and carbon when tri-mingled with Innegra and Kevlar.

Figure 8.9 shows the response of E-glass and carbon when used in non-crimped and crimped structures. Both materials experienced a change in kinetic energy that was relatively comparable between the non-crimped verse crimped structures. For E-glass, the non-crimped material experienced a slightly greater change in kinetic energy compared to the crimped material (p=0.524) which was not statistically significant; however, this differs from carbon where the crimped material experienced a slightly greater change in kinetic energy compared to the non-crimped material (p=0.523) which was not statistically significant. This could be due to the differences in the stiffness of the E-glass and carbon fibers.

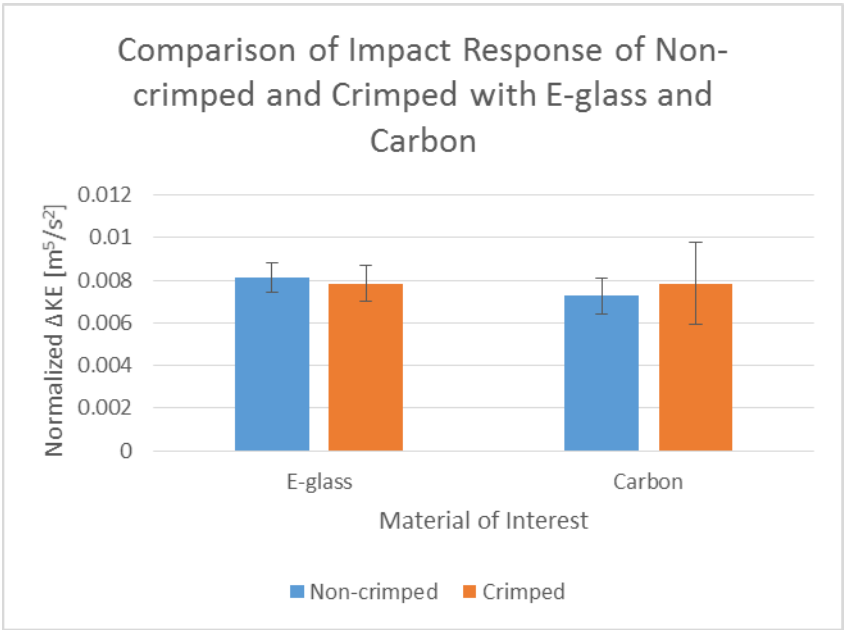


Figure 8.9 Comparison of the change in kinetic energy (normalized by density) of E-glass and carbon in non-crimped and crimped composites.

Figure 8.10 specifically looks at a non-crimped composites. It compares two raw materials, E-glass and carbon. When both materials are crimped, E-glass experiences the greater change in kinetic energy compared to carbon (p=0.0794); however, the change in kinetic energy between E-glass and carbon is not statistically significant.

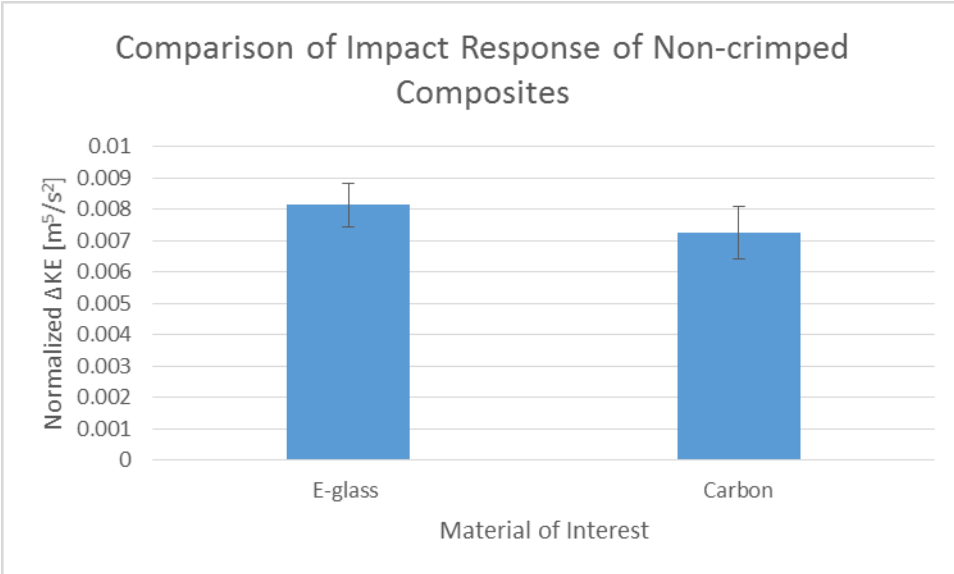


Figure 8.10 Comparison of the change in kinetic energy (normalized by density) of glass and carbon in non-crimped composites.

Figure 8.11 examines the different between using two different types of carbons, standard modulus carbon verse intermediate modulus carbon, in a commingled hybrid yarn. The Intermediate carbon is known for being stiffer than the standard carbon. During impact testing, the intermediate carbon experienced a greater change in kinetic energy compared to the more flexible standard modulus carbon (p=0.0085), and the differences were statistically significant.

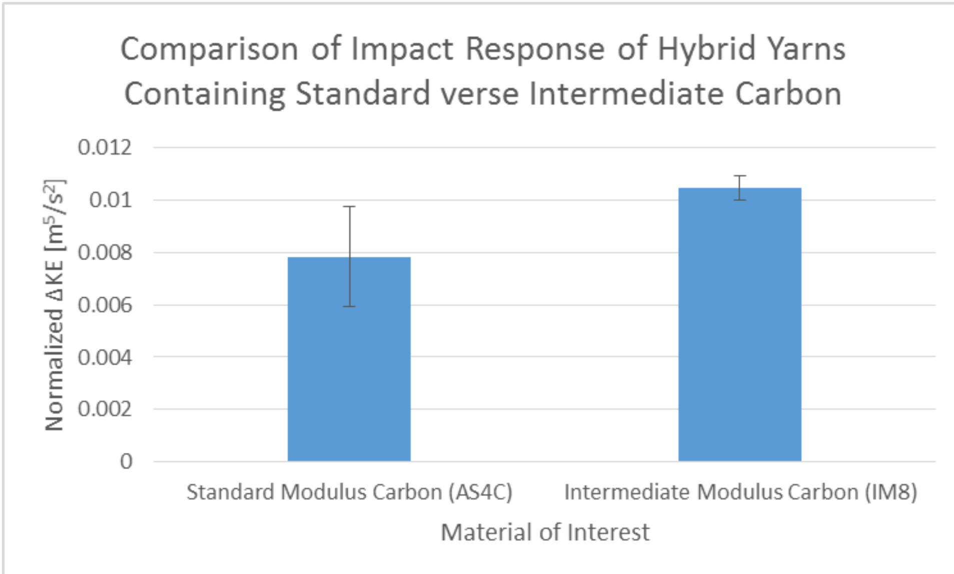


Figure 8.11 Comparison of the change in kinetic energy (normalized by density) of standard and intermediate carbons used in hybrid commingled yarns.

Figure 8.12 examines the response of commingled hybrid yarns containing S-glass and E-glass in crimped composites. When subject to impact, S-glass experienced the greater change in kinetic energy compared to E-glass (p=0.0140), and the differences were statistically significant.

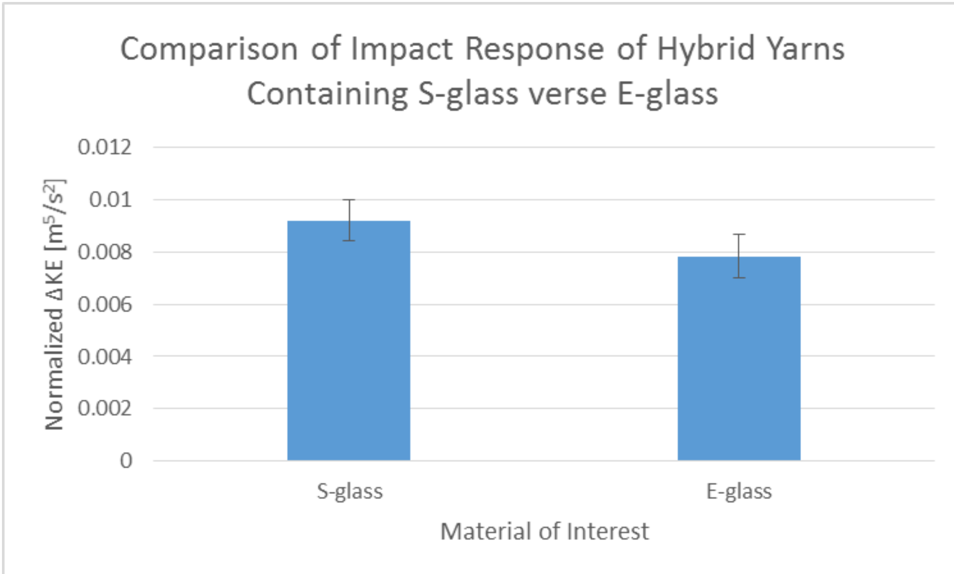


Figure 8.12 Comparison of the change in kinetic energy (normalized by density) of S-glass and E-glass used in hybrid commingled yarns.

8.3. Tensile Testing

Tensile testing was performed by Innegra Technologies in order to obtain the flex strength and flex modulus of the composite materials in comparison to polycarbonate and ABS. The results were reported to Clemson University, and the data can be seen in Figure 8.13 and 8.14. Figure 8.13 shows that eighteen of the twenty-two samples had a flexural strength greater than polycarbonate. Samples 1, 8, 22, and 24 have flexural strengths equal to or less than the standard polycarbonate. When the data in Figure 8.13 is normalized based upon density, only Samples 22 and 24 had flexural strengths less than polycarbonate. From Figure 8.14, all twenty-two composites tested had a flexural modulus greater than polycarbonate, and this holds true when the flexural modulus was normalized by density as well.

Additional graphs comparing the change in kinetic energy and displacement between raw materials and composites containing hard verse soft surfaces can be found in Appendix C.

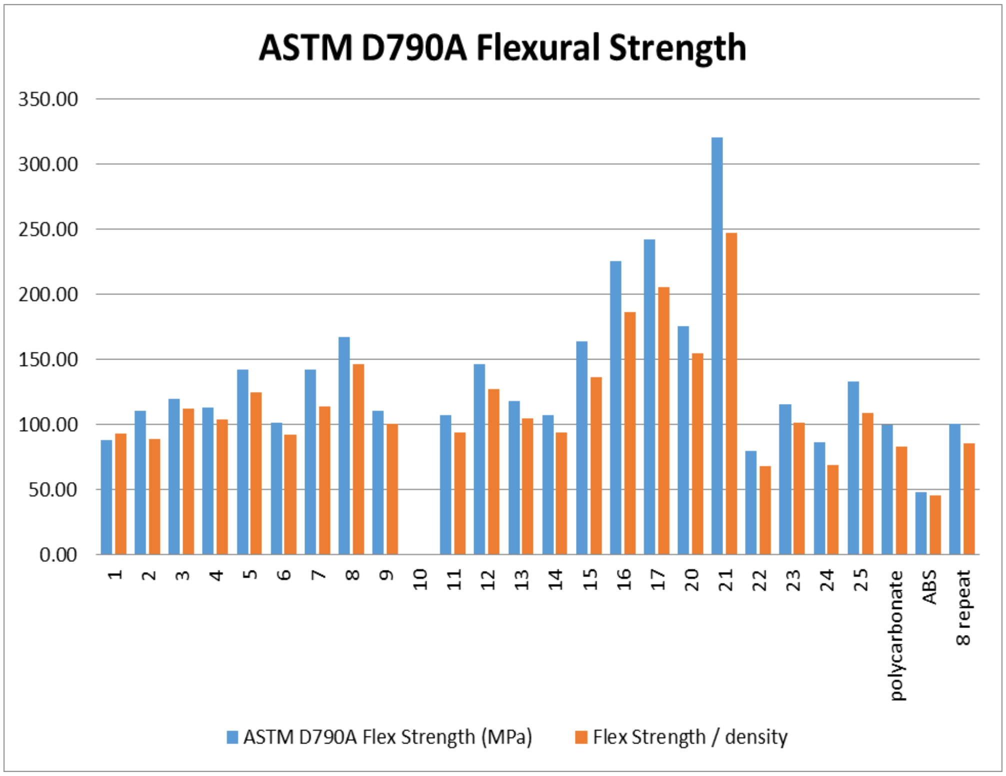


Figure 8.13 Flexural strength data of all composite specimens compared to polycarbonate and ABS (provided by Innegra Technologies). Note: Sample 8 testing was repeated due to inconsistent data.

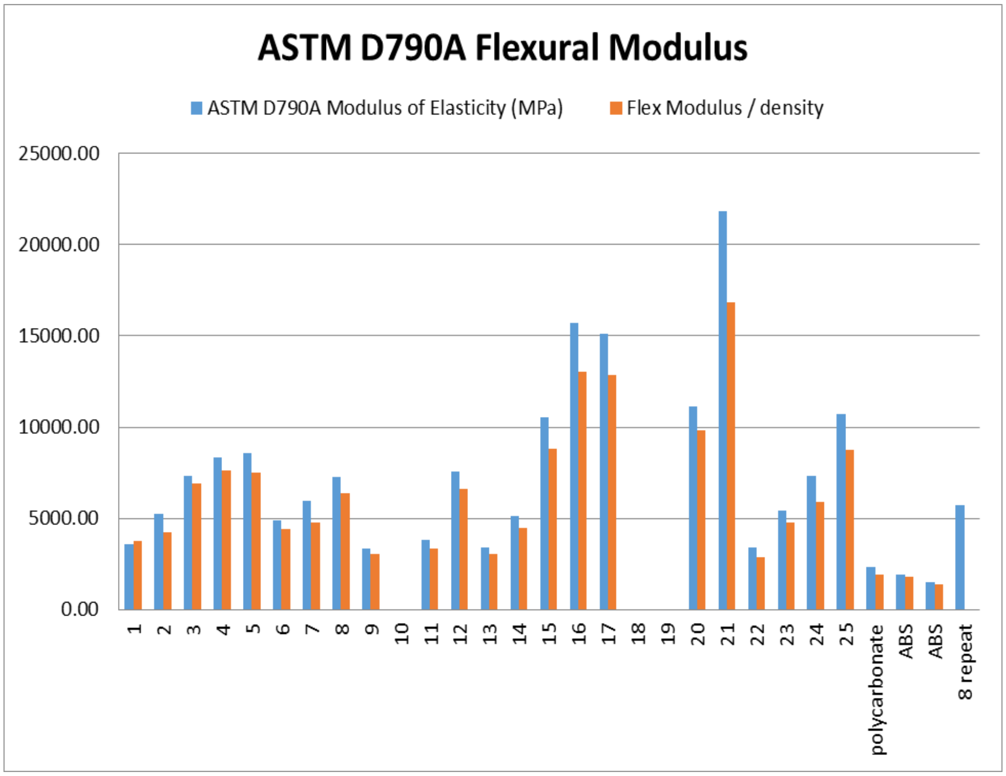


Figure 8.14 Flexural modulus data of all composite specimens compared to polycarbonate and ABS (provided by Innegra Technologies). Note: Sample 8 testing was repeated due to inconsistent data.

CHAPTER NINE

DISCUSSION

The results presented in this thesis show trends that both agree and disagree with what is presented in the literature on low velocity impact testing of flat panel composites. Explanations for the trends with literature are described and evaluated in order to relate the data presented in literature to the results of Phase I testing.

9.1. Dynamic Drop Weight Impact Testing

The use of composites in low velocity impact conditions have proven to have attractive energy absorbing properties. To evaluate the performance of the energy absorbing capabilities of the composites provided, the composite materials were subject to impact conditions, and the responses were evaluated and analyzed.

Raw Material: Impact Response

Numerous different raw materials have been used to construct the composites. The behavior of each composite was different in impact conditions depending on the type of hybrid (co-woven or commingled), crimped or non-crimped, the surface stiffness of the composite, and the weight percent of each raw material that is present in the complete composite. Because there is so much variability to the response of the composite, relationships between the data presented in literature does not completely correlate with the results of this study; however, several relationships and discrepancies with the data can still be made.

One of the prominent materials used in each composite was the Innegra fiber. The Innegra fiber is a commingled polypropylene fiber with other blends of carbon, basalt, and glass. The polypropylene fiber has proven to be a good candidate for impact conditions requiring energy absorption due to its excellent fatigue characteristics. Previous literature on testing of the commingled glass fiber polypropylene done by Reyes et al. has shown that nearly 75% of the impact energy was absorbed by the woven composite when subject to 16 J of energy [52]. Results of the study performed by Reyes et al. compared to the data obtained in this study, verifies that the use of the Innegra fiber containing polypropylene is a good fiber to use for energy absorption under impact conditions.

The authors of Reyes et al. study attributed the substantial energy absorption in the glass fiber polypropylene composite due to the composite structure being woven verse unidirectional, and suggests for the construction of composites to be woven structures for applications requiring substantial energy absorption [52]. From the study performed by Reyes et al., it is important to relate this to the polymer composites being tested in this study. For football helmet applications, it is the goal for the outer shell to absorb as much energy as possible. A significant amount of energy absorption in the outer shell means less energy is transferred to the inner foam padding. When making modifications to the designs of the composite structures to be tested in future phase of this complete study, testing a woven structure verse unidirectional composite structure must be taken into account. This will allow researchers to compare the energy absorption between the two. Also, the composite material used in the external shell cannot be too stiff. A material that is exceptionally stiff will lead to increased linear and rotational head accelerations experienced by the player which could potentially promote the use of the helmet as a weapon within the sport.

In order to evaluate the response of the materials used in the composite structures, several studies have been evaluated. Hosseinzadeh et al. tested carbon fiber composites, glass/carbon composites, and glass composites impacted with a hemispherical indenter at energies of 30, 50, and 100 J (2.5 kg and 5 kg). The results of the study showed the composites exhibit different damage characteristics depending upon the impact event. Glass fibers were used because these fibers are capable of undergoing a range of impact energies despite the fact that they are less strong compared to other composites, and carbon fibers were used because these fibers exhibit exceptional strength in low velocity impacts, and they have a low density as well. However, the downside to carbon fibers is their brittleness [19]. Because carbon fibers have a low density, this makes them attractive for the use in the outer shell of the football helmet. These fibers have the potential to decrease the weight of the external shell and overall weight of the helmet.

In the Hosseinzadeh et al. study, Glass Woven/Epoxy, Carbon/Epoxy, and Glass/Carbon Woven/Epoxy (Hybrid) were all compared. From the results, Glass/Epoxy demonstrated the most stability, however, the downside to this structure was that it significantly increased the weight. Carbon/Epoxy demonstrated good “structural resistance” when subject to impacts at low velocity, however, as velocity increased, the structure collapsed. Carbon/Glass/Epoxy (hybrid) was beneficial because it exhibited beneficial properties under low impact due to the carbon fibers, and was more stable than Carbon/Epoxy under high impacts due to the glass fibers. Looking at the weight between structures, carbon has the lowest weight [19]. These results are consistent with the results of our study. Figure 8.1 shows that comparing the density between Samples 2 and 3, Samples 15 and 16, and Samples 22 and 23, which compare glass and carbon directly, Samples 2, 15, and 22 contain the higher density than Samples 3, 16, and 23, meaning that the weight of the glass used in the composite increases the density. When evaluating the energy absorption for the composites, Figure Samples 2, 15, and 22 (all containing the glass) experienced a greater change in kinetic energy than its carbon counterparts which is consistent with literature. However, when the change in kinetic energy experienced by each composite was normalized by density, Samples 2 and 15 still experienced a greater change in kinetic energy than Samples 3 and 16, but Sample 23 (containing carbon) experienced a greater change in kinetic energy than Sample 22 (containing glass). One reason for this could be due to the fact that Samples 22 and 23 were fabricated differently compared to the other samples. Samples 22 and 23 were made of a non-crimped fabric, whereas the other samples were made of a crimped fabric. The use of a crimped verse non-crimped fabric could change the properties of energy absorption.

Another interesting point to note is that when visually inspecting the impacted specimen. Sample 3 and 23 (carbon) had more visible damage compared to Samples 2 and 22 (glass) (see Figures C.13 and C.14), which is consistent with the Hosseinzadeh et al. results. Glass appears to have less external damage because most of the damage is internal which sacrifices the mechanical strength of the composite. This must be taken into account when designing the composite for the use in the outer shell of the football helmet. Although glass performs well under a single impact condition, it must be taken into account how the use of glass will hold up over time when subject to numerous football impacts.

When looking at the impact response of Kevlar, E-glass, and carbon composites, Beaumont et al. have found that composites containing Kevlar have the ability to absorb more energy compared to those composites containing E-glass and carbon fibers [50, 67]. Another study also found that when Kevlar and S-glass fibers were combined to form a composite, these composites absorb nearly five times more energy than carbon composite structures [50].

The data found in literature are not completely supported by the results of the data presented in this thesis. Samples 11 and 12 from the study were both tri-mingled hybrid yarn with one of the materials being Kevlar. Figure 8.2 shows that Sample 11 did not experience a greater change in kinetic energy compared to the standard polycarbonate, and its kinetic energy change is on the low side compared to the results. Sample 12 did experience a greater change in kinetic energy compared to polycarbonate; however, in comparison to the other composite samples, it was not a top performer in relation to the other raw materials used. There are numerous reasons for this. Although the same type of Kevlar (Kevlar 49) were used in both studies, one initial reason for differences could be due to the use of a differing impact shape (pointed end) in the Beaumont et al. study compared to the hemispherical impactor used in this study. Another reason for the difference could be that this study investigates a trimingled hybrid yarn. The type of hybrid composite tested in the study performed by Beaumont et al. is not specified. Also, a final difference was that only seven plies were used to construct the Kevlar composites of interest in this study compared to eight plies in the Beaumont et al. study. A difference in the number of plies, and therefore weight percent of Kevlar, could be a potential reason for better energy absorption properties in the Beaumont et al. study.

Kevlar can be used as an alternative to carbon fibers in a composite. Kevlar fibers have a higher modulus and increased extensibility when compared to carbon fibers [68]. Marom et al. found that Kevlar composites absorbs two times greater impact energy compared to carbon composites [69]. When comparing Sample 12, which contains a tri-mingled Kevlar/carbon/Innegra hybrid yarn, to Sample 7 and 14, which contain a commingled carbon-Innegra hybrid yarn, Sample 12 experiences a greater change in kinetic energy compared to the composites containing solely carbon. Further testing is needed to make definitive conclusions, but in these specific composite samples, incorporating Kevlar with carbon fibers into a composite demonstrates increasing energy absorbing capabilities of the composite.

Hard Surface verse Soft Surface Composites

Evaluating the response of energy absorption after impact of both the hard and soft surface composites in this study had varying results. The softer surface in Samples 3 (soft) and 4 (hard) when comparing co-woven Innegra and carbon demonstrate the softer surface experiencing a greater change in kinetic energy. The trend is consistent with Samples 22 (soft) and 24 (hard) comparing non-crimped Innegra and glass, as well as Samples 23 (soft) and 24 (hard) comparing non-crimped Innegra and carbon. The harder surface in Samples 7 (soft) and 8 (hard) when comparing commingled Innegra and carbon demonstrate the harder surface experiencing a greater change in kinetic energy.

The results seen in this study demonstrates that sometimes due to the significant amount of raw parent material used, the properties of the parent material within the composite will overpower the response of the surface stiffness, as seen in Samples 7 and 8 which contain a significant amount of carbon. Since carbon is stiff, this property dominates the impact response because a large percent of the sample is composed of carbon fibers.

Impactor Shape

For the dynamic drop weigh impact tests performed in this study, a 0.625" hemispherical indenter was used according to ASTM D7136-12. The choice to use this small of an impactor was decided upon in order to be compliant with current ASTM standards. Since the preliminary testing involved testing a significant amount of samples to down-select from, the primary goal was to evaluate the impact performance of the overall composite. Although this impactor size is not representative of the radius of curvature of a football helmet, future studies have been designed to use an impactor that is more representative of the football helmet (see Appendix D, Figure D.1 and D.2). Because this study choose to use a significantly smaller impactor for the preliminary studies, there are limitations in the data provided as to be related to the performance of these materials under impacts more strongly correlated to football impacts. The impactor shape does dictate the response of the composite under impact conditions.

Several studies have shown that the radius and shape of the indenter will significantly influence the internal damage that the composite undergoes. This is because the contact area and contact pressure are dependant on the impactor tip radius. Research has shown that as the radius of the impactor increases, the composite must be subject to significantly greater impact energies for damages consistent with smaller impactors to occur. This is due to an increased contact force throughout the material of the larger radius impactor compared to a more concentrated load in a smaller area for the smaller radius impactor. The differing responses of the composite under variable impactor radii also depends on the thickness of the sample. Thinner samples are less stiff compared to thicker samples, and therefore, thinner samples experience less contact force due to the increased flexural deformation (compared to thicker composite samples) experienced upon impact [70–72].

This information proves that there will be differing responses to the composites with the use of the new impactor that is more representative of the football helmet. It is hypothesized that composites will be able to undergo energies greater than the initial 20 J used for preliminary testing and not experience as much damage until subject to higher energy levels. However, the exact response of each composite will be dependent on the raw material used, as well as the cross-sectional thickness of the samples. The failure modes experienced between composites will differ between samples due to thickness with thicker samples experiencing delamination damage due to the high contact forces from increased stiffness and thinner samples experiencing fiber breakage due to flexural deformation. These differences in internal damages must be evaluated, analyzed, and taken into account when designing the appropriate thickness to use in the outer shell of the football helmet.

Composite Helmets

The use of composite helmets are being seen in other applications involving impact such as motorcycle and military helmets. Kostopoulos et al. evaluated three different composite motorcycle shells: glass fiber, carbon fiber, and Kevlar fiber. The results show that Kevlar fiber shells experienced the longest duration as well as the lowest peak acceleration values compared to carbon fiber and glass fiber shells. Kevlar shells also gave data that resulted in the lowest HIC value (1700) compared to carbon shells (2004) and glass shells (2008). Current research with the use of Kevlar in military helmets is on-going [73–75].

This data can prove to be beneficial when determining which samples will be down-selected for Phase II testing and eventually Phase III testing. However, it must be taken into account the type of impacts that specific helmets are used for. Football helmets must be able to withstand multiple impacts; whereas bike and military helmets usually only function for single impact events. After a single impact, these helmets need to be replaced, which is not the case for football helmets. These variables need to be taken into account when investigating the materials used in current composite helmets. Overall, exploring literature for information on what type materials make up composite helmets currently on the market, and in what specific applications these composite shells prove to be beneficial can researchers involved in this study the competitive advantage over all existing composite helmets currently on the market.

CHAPTER TEN

RECOMMENDATIONS FOR FUTURE RESEARCH

The primary focus of the research presented in this thesis involved designing the experimental protocol and performing preliminary testing which made up Phase I of the complete study. The entire study is composed of three phases, and many recommendations to the design and testing of protocol with respect to the continuation of Phase II and III as well as new ideas for future research will benefit the results of the study.

Phase II testing involves performing dynamic drop weight impact testing using the down-selection of the original twenty-two flat panel composite specimens. The top ten performers will be impacted with a hemispherical impactor with dimensions that are more representative of the American football helmet [radius of 4"]. Previously, in Phase I, due to the large amount of specimens to test, each specimen was only impacted once in order to obtain preliminary data on the response of the composites under impact conditions. For Phase II, since significantly less samples will be tested, it would be beneficial to perform multiple impacts at 20 J of impact energy on each flat panel composite specimen. Because composite materials absorb energy by fracturing internally, it will be important to evaluate the structural mechanics of how the composite performs after multiple impacts have occurred. It is suggested that three impacts be used to evaluate the integrity of each composite specimen.

Another suggestion for Phase II testing is that three different types of resins be used with the top ten specimen configurations. The use of different resins have varying effects on the impact properties of the composite. It would be beneficial for these composites containing the new resin to undergo multiple impacts as well to evaluate the performance of the mechanical structure of the composite.

Phase I did not focus on imaging the impacted specimens after impact events. For future testing, it will be beneficial to have the impacted specimens sent to a laboratory to undergo x-ray analysis. This will allow the internal fracture characteristics to be observed to help understand the damage characteristics, and this will aid in further narrowing the configurations for Phase III testing. It will also aid in an understanding of how specific hybrid yarns and hybrid fabrics respond differently to impact energies.

Another recommendation to Phase II testing is that the specimen be subject to varying impact energies. It will be beneficial to see how the raw materials in the composite structure respond at different impact energies. Prior literature suggests that the response and properties of the materials vary based upon the impact energy. This also relates to American football because the player wearing the helmet with the shell made of a composite material will be subject to differing impact energies based upon the position played and the type of hits endured. It is useful to demonstrate that the composite material that will make up the shell can withstand multiple different impact energies.

Phase III testing focuses on using the top three composite configurations from Phase II to be used in the fabrication of the outer shell of the football helmet. This final phase involves performing football helmet testing according to NOCSAE Standards to evaluate the performance of the composite football helmet. A Hybrid III Head and Neck Assembly will be equipped with a composite football helmet, and drop weight impact tests will be performed.

There exists an extensive amount of research on the cause of mTBI. An easy and exact explanation is not available to current researchers. Numerous studies have suggested that receiving an mTBI from a football head impact is not only associated with linear accelerations but with rotational accelerations experienced by the player as well. Currently, there are no standards or mathematical models that exist to measure the rotational response of the performance of a football helmet. For Phase III testing, it is suggested that in order to better understand the response of the composite materials under rotational accelerations that impact tests to the helmet must involve impacts that cause rotational accelerations. Rotational accelerations should be measured and compared to a standard Hybrid III head impacted with no helmet to compare and evaluate the effects of how a helmet responds to this event.

The recommendations for future work in the complete study that have been provided will aid in the discovery of which composite specimen will be the best performer for use in the outer shell. These suggestions are offered in hopes to aid in the discovery of a composite which will decrease the linear and rotational acceleration experienced by the football player by better distributing the impact force and dissipating and absorbing energy.

CHAPTER ELEVEN

CONCLUSION

From the preliminary testing completed in Phase I of a three phase study, there are significant differences between the impact responses between each composite configuration. Based upon the results in comparison to polycarbonate, the current material used in the outer shell of the football helmet, the top ten performers have been chosen to enter Phase II testing.

From the three aims of the study, all have been used to aid in the design of composite configurations and testing of these composites to evaluate the performance under dynamic drop weight impact conditions. The first aim was accomplished, and seventeen of the twenty-two configurations were fabricated with a density that was equal to or less than the density of the standard helmet shell material, polycarbonate. The second aim was accomplished and dynamic drop weight impact testing on composite specimens were performed for data analysis. The third and final aim of Phase I testing was also accomplished. Based upon the dynamic drop weight impact test results, seven of the twenty-two composite configurations did absorb a greater amount of kinetic energy compared to polycarbonate, and six absorbed comparable amounts, although slightly less, compared to polycarbonate.

Further testing in Phase II and III needs to be conducted for a better understanding of the impact properties and responses of the raw materials used in the composites. Improvements to experimental protocol that has been proposed for Phase II and III should also be taken into consideration to aid in the ultimate goal of the complete study: The selection of a composite to be used in the outer shell of the football helmet that performs the best under impact conditions representative of the American football hit.

CHAPTER TWELVE

APPENDICES

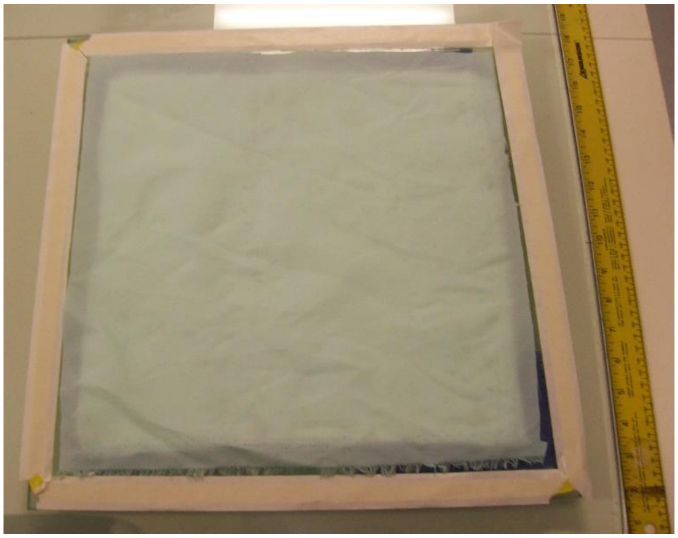
Appendix A

Panel Fabrication Process: Vacuum Infusion

Adapted from Russ Emanis:

1. Cut 18” by 18” sheets of the appropriate fabrics for the laminate stack.
2. Tape fabric edges are all taped prior to stacking.
    a. This ensures that there will be no fiber misalignment before or after cutting the panels.
    b. Also, be mindful of the fiber orientations that the fabric is being cut at: 0/90° or ±45° orientations.
3. Arrange each 18” by 18” fabric in the precise order according to the Panel Planning Sheet.
    a. In order to ensure that all plies are accounted for, check off each ply on the Panel Planning Sheet as the layer is added to the stack of fabrics.
    b. Panel Planning Sheet gives the specifics for the order to each layer of fabric to be used and the correct orientation of fabrics.
4. Place the laminate stack (collection of cut fabrics arranged according to the Panel Planning Sheet) onto a glass surface that has been appropriately cleaned.
5. Apply tacky tape to surround the fabric on the glass surface.

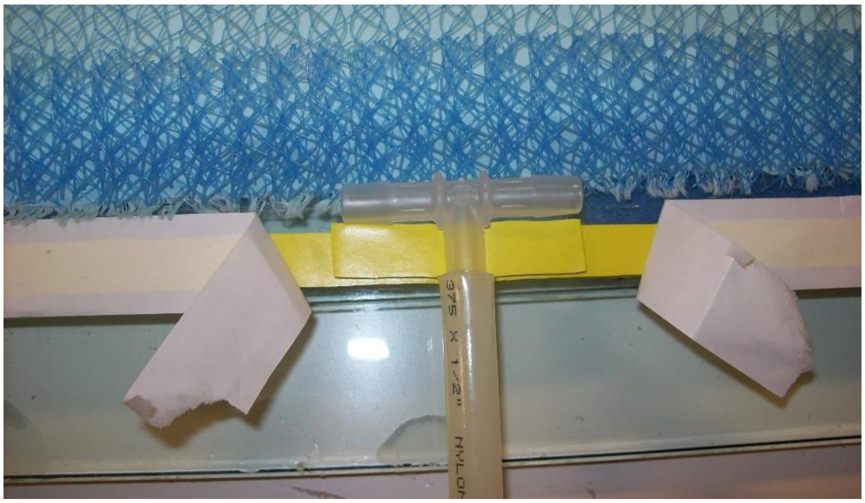
6. Tape three edges of the laminate stack to the glass surface.
7. Cut a 16” by 26” piece of peel ply to be placed on top of the laminate stack.
    a. Note: This peel ply is placed on top of the already taped laminate stack, and the peel ply is not taped to the glass surface.
8. Center the layer of peel ply over the laminate stack. Ensure that there is a roughly 0.5”-1.0” overhang of peel ply on each side of the taped laminate stack.
    a. This overhang over the taped edges will create a resin break area and flow path.



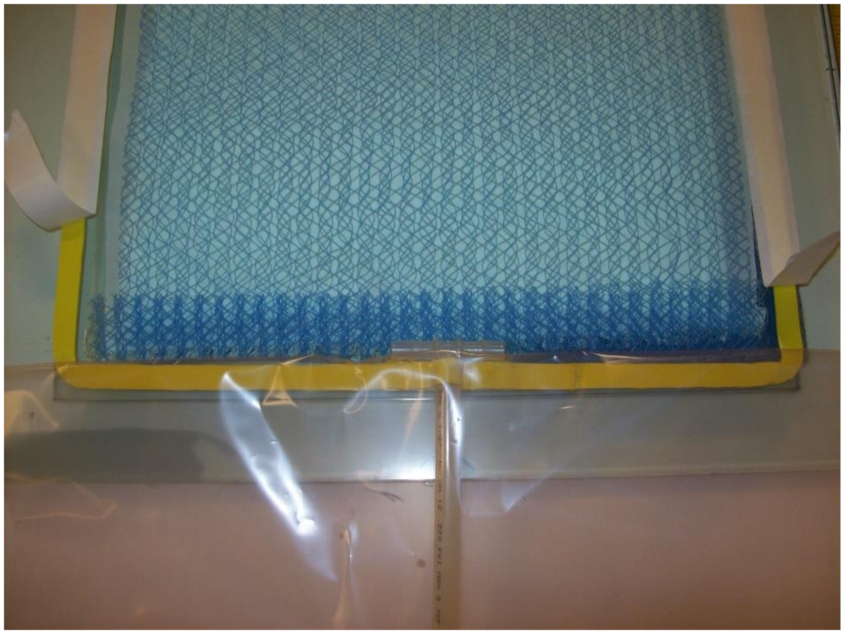
9. Cut a 16” by 18” piece of green medium flow media (bleeder scrim).
10. Center the layer of green medium flow media (bleeder scrim) over the peel ply allowing a 1.0” overhang on each side.

11. Tape the layer of green medium flow media down to the glass on every side.
12. Attach all “plumbing” for vacuum infusion process, and tape it in place to secure it.

a. Note: One end of plumbing will be resin feed, and the other end of the plumbing is the vacuum. The vacuum is placed at the end of the laminate stack that is not taped to the glass.



13. Apply sealing tape to both the vacuum and resin inlets.
14. Clean the glass around the laminate stack.
    a. This ensures that there are no excess fibers or debris that will be incorporated in the panel fabrication process.
15. Cut a 26” by 26” vacuum bag from the bagging film.
16. Place the vacuum bag centered over the ply stack.



17. Starting at the resin feed inlet side, carefully remove the paper cover from the tacky tape surrounding the laminate.
18. Adhere the exposed piece of tacky tape to the vacuum bag film.
19. Pull the vacuum bag towards the feed inlet.
    a. Note: Be sure to allow a 2" pleat near the feed inlet (top middle of the pleat) so that a very small hole may be cut over the top of the feed inlet.
20. Once the hole is cut over the top feed inlet, carefully stretch the new vacuum bag hole over the inlet.
21. Seal the vacuum bag hole and inlet interface plumbing area with tacky tape.
22. Continue to adhere the rest of the sides of exposed tacky tape and vacuum bag together.
    a. Ensure that the newly made vacuum bag is completely sealed on all sides.
23. Attach and clamp a 14" tube on the barb of the resin inlet side of the vacuum bag.

a. This ensures that it will not leak when under vaccum.

24. Attach and clamp a 20” tube to the vacuum side of the vacuum bag.

25. Connect the 20” vacuum tube to the vacuum source.

26. Turn on the vacuum and allow for the air to be extracted from the vacuum bag over the ply stack.

    a. Note: Check for leaks in the vacuum bag, and fix leaks immediately.

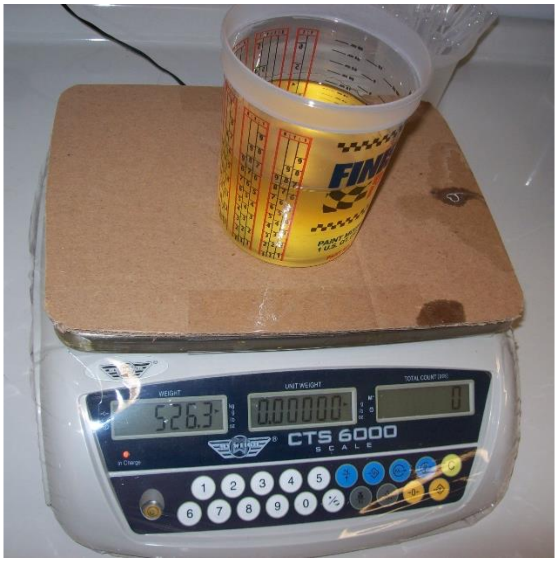
27. Leave the ply stack under vacuum exposure for no less than 30 minutes.

    a. Note: This ensures that all moisture has been evacuated from the ply stack.

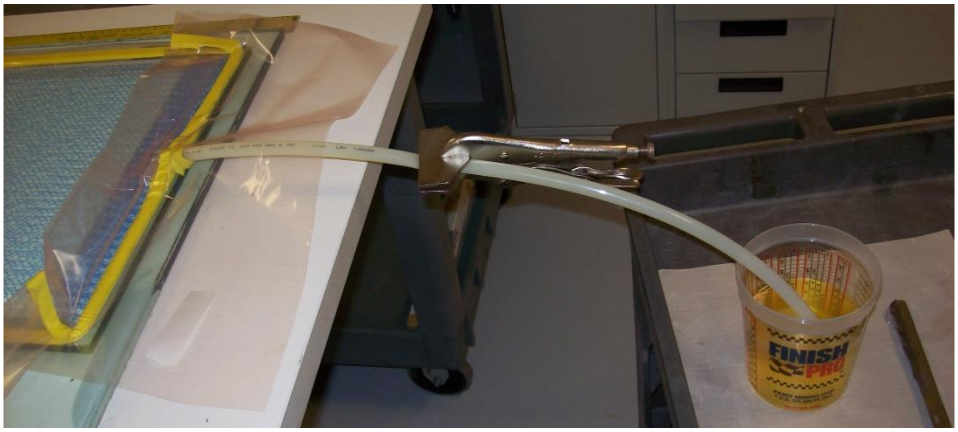
28. Check to ensure that the temperature and pressure are in the optimal temperature range for infusion (80-85 °F and no less than 27 inch Hg).

29. Mix the resin to be used in the process.

    a. Resin components must be measured according to weight for accuracy.



30. Release the resin into the ply stack and allow it to flow 1” up the ply stack.



31. Slow the flow of resin.

32. Once the resin has travelled 17”, stop and clamp the resin line.

33. Maintain the vacuum level until the part has gelled so that the vacuum may pull off the excess resin.

<u>Appendix B</u>

<u>Shock Accelerometer Specifications</u>

	ENGLISH	SI	
Performance			
Sensitivity (±10 %)	10 mV/g	1.02 mV/(m/s²)	
Measurement Range	±500 g pk	±4905 m/s² pk	
Frequency Range (±5 %)	1 to 10000 Hz	1 to 10000 Hz	
Frequency Range (±10 %)	0.7 to 18000 Hz	0.7 to 18000 Hz	
Frequency Range (±3 dB)	0.35 to 30000 Hz	0.35 to 30000 Hz	
Resonant Frequency	≥70 kHz	≥70 kHz	
Broadband Resolution (1 to 10000 Hz)	0.005 g rms	0.05 m/s² rms	[3]
Non-Linearity	≤1 %	≤1 %	[1]
Transverse Sensitivity	≤5 %	≤5 %	[2]
Environmental			
Overload Limit (Shock)	±10000 g pk	±98100 m/s² pk	
Temperature Range (Operating)	-65 to +250 °F	-54 to +121 °C	
Base Strain Sensitivity	≤0.002 g/με	≤0.02 (m/s²)/με	[3]
Electrical			
Excitation Voltage	20 to 30 VDC	20 to 30 VDC	
Constant Current Excitation	2 to 20 mA	2 to 20 mA	
Output Impedance	≤100 Ohm	≤100 Ohm	
Output Bias Voltage	8 to 12 VDC	8 to 12 VDC	
Discharge Time Constant	0.5 to 2.0 sec	0.5 to 2.0 sec	
Settling Time	<5 sec	<5 sec	
Spectral Noise (1 Hz)	2800 μg/√Hz	27468 (μm/sec²)/√Hz	[3]
Spectral Noise (10 Hz)	700 μg/√Hz	6867 (μm/sec²)/√Hz	[3]
Spectral Noise (100 Hz)	180 μg/√Hz	1766 (μm/sec²)/√Hz	[3]
Spectral Noise (1 kHz)	64 μg/√Hz	628 (μm/sec²)/√Hz	[3]
Physical			
Size - Height	0.43 in	10.9 mm	
Weight	0.07 oz	2.0 gm	[3]
Sensing Element	Quartz	Quartz	
Size - Hex	0.31 in	7.9 mm	
Sensing Geometry	Shear	Shear	
Housing Material	Titanium	Titanium	
Sealing	Welded Hermetic	Welded Hermetic	
Electrical Connector	5-44 Coaxial	5-44 Coaxial	
Electrical Connection Position	Side	Side	
Mounting Thread	5-40 Male	5-40 Male	
Mounting Torque	8 to 12 in-lb	90 to 135 N-cm	

All specifications are at room temperature unless otherwise specified.

Appendix C

Additional Results

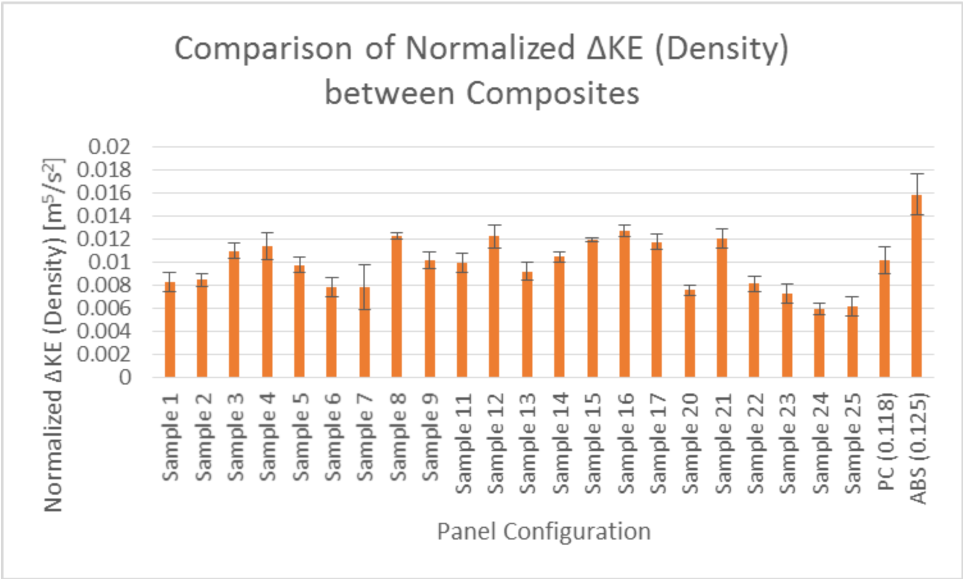
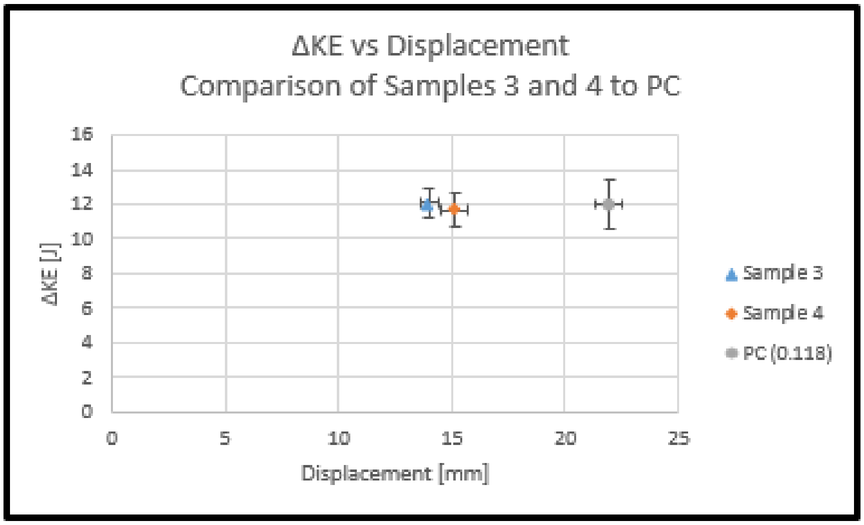


Figure C.1 Comparison of the change in kinetic energy (normalized by density) experienced by composites, polycarbonate, and ABS from an impact event.



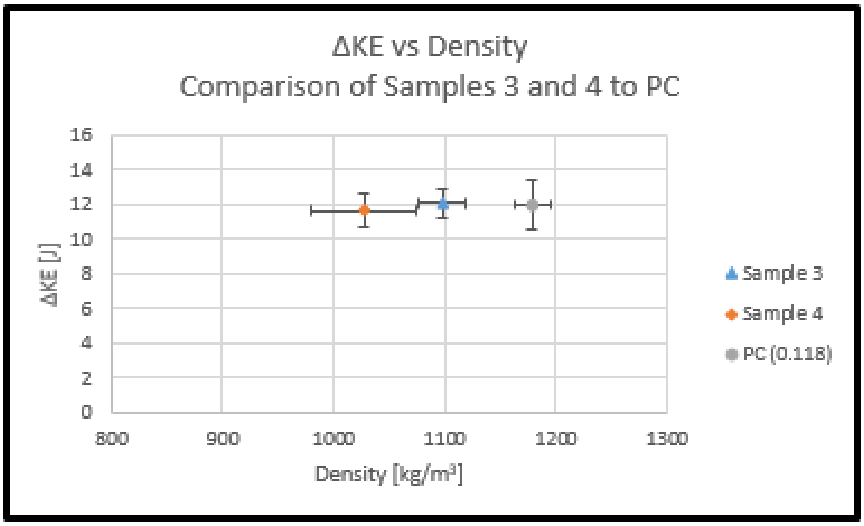


Figure C.2 Representation of the ΔKE related to density for composite samples 3 and 4.

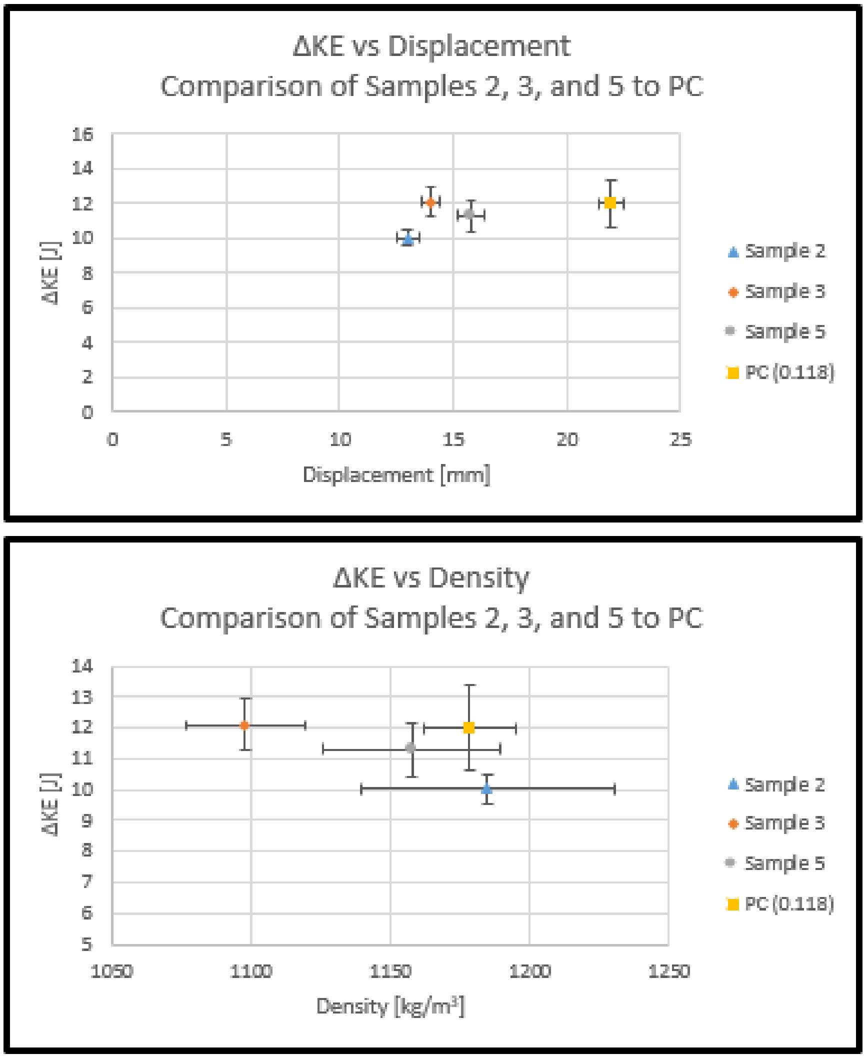
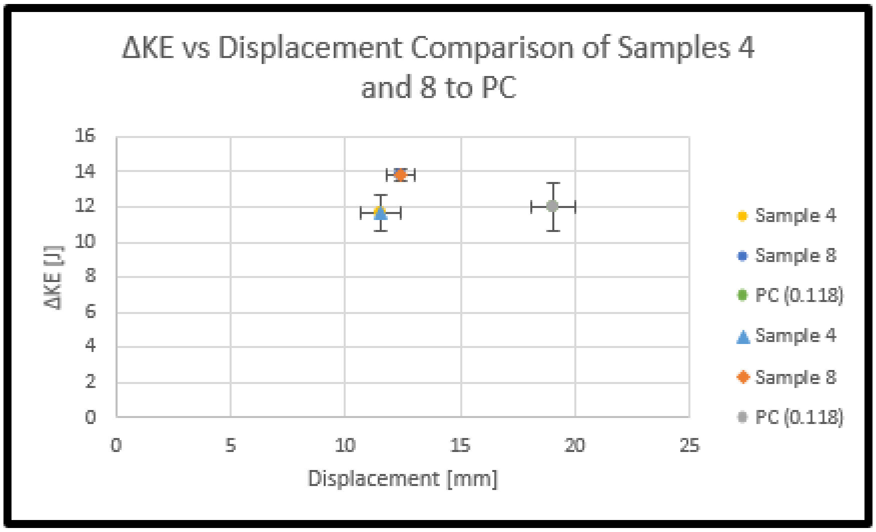


Figure C.3 Representation of the ΔKE related to displacement and density for composite samples 2, 3, and 5.



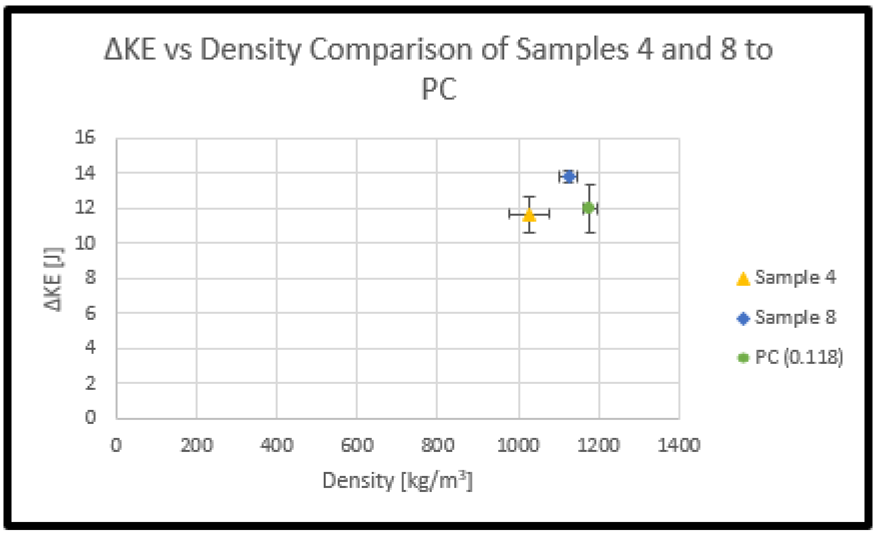


Figure C.4 Representation of the ΔKE related to displacement and density for composite samples 4 and 8.

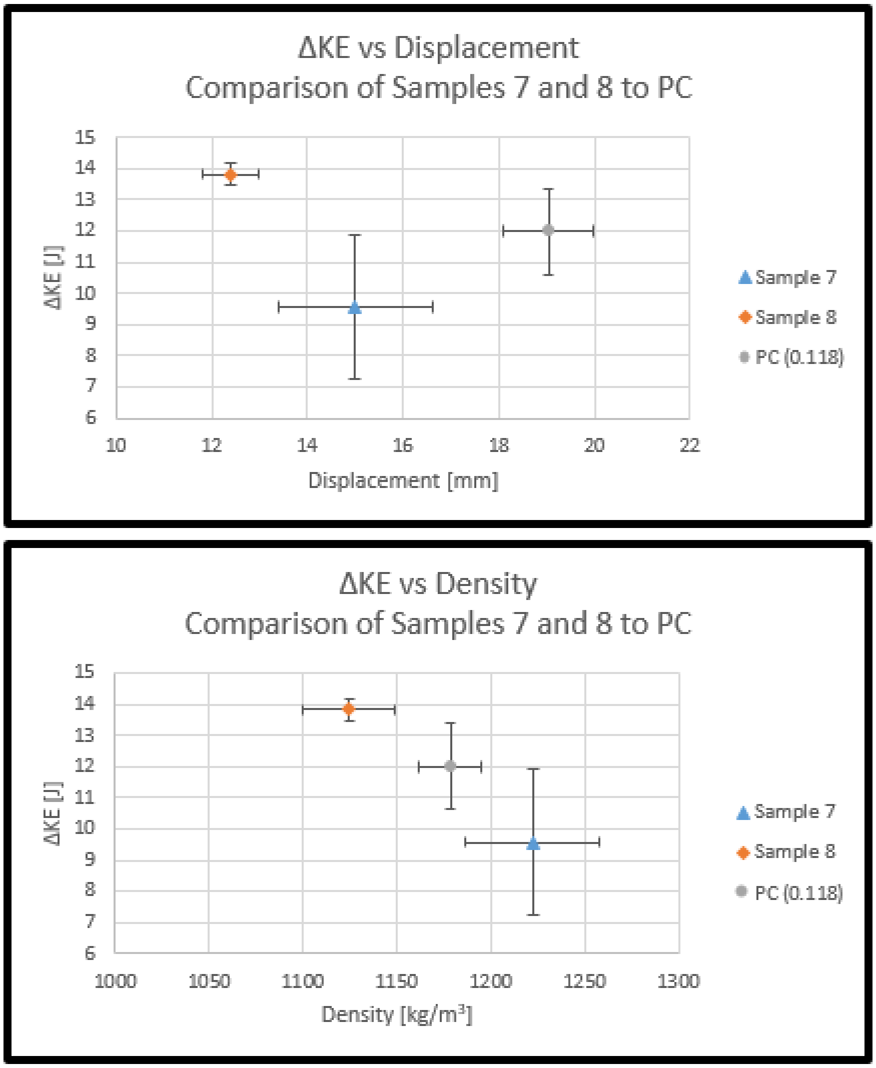


Figure C.5 Representation of the ΔKE related to displacement and density for composite samples 7 and 8.

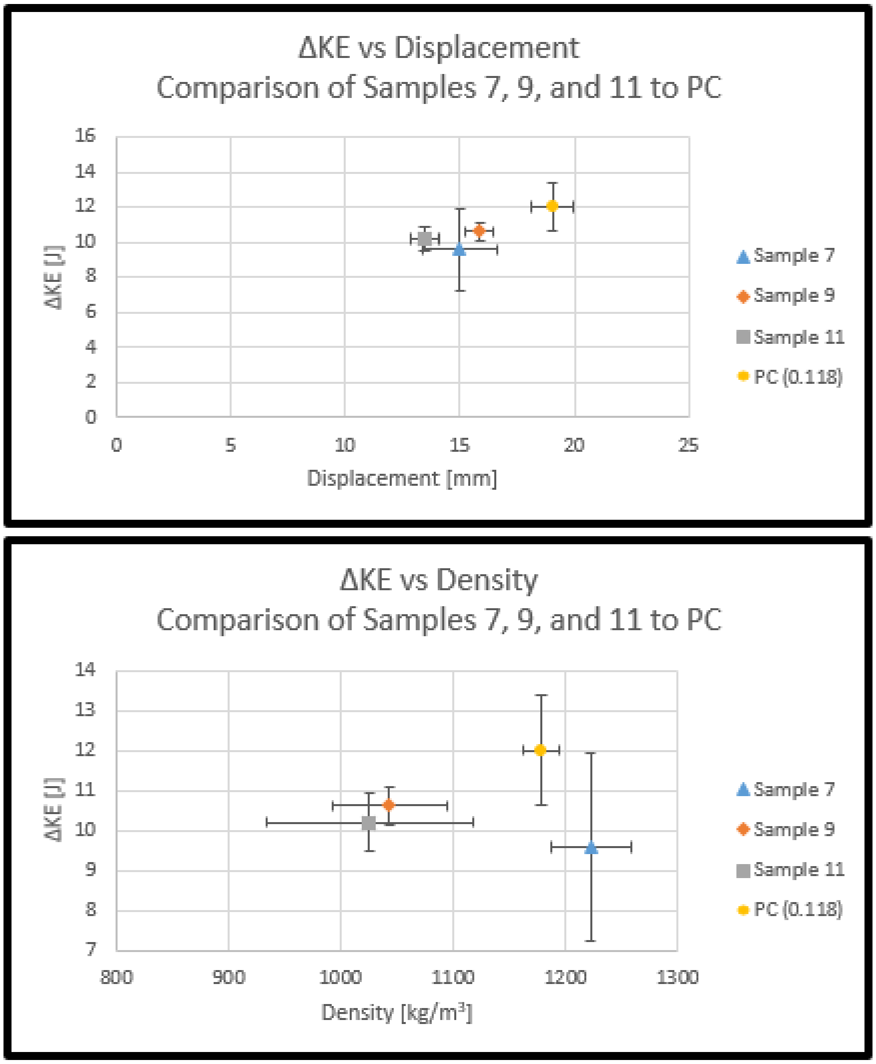


Figure C.6 Representation of the ΔKE related to displacement and density for composite samples 7, 9, and 11.

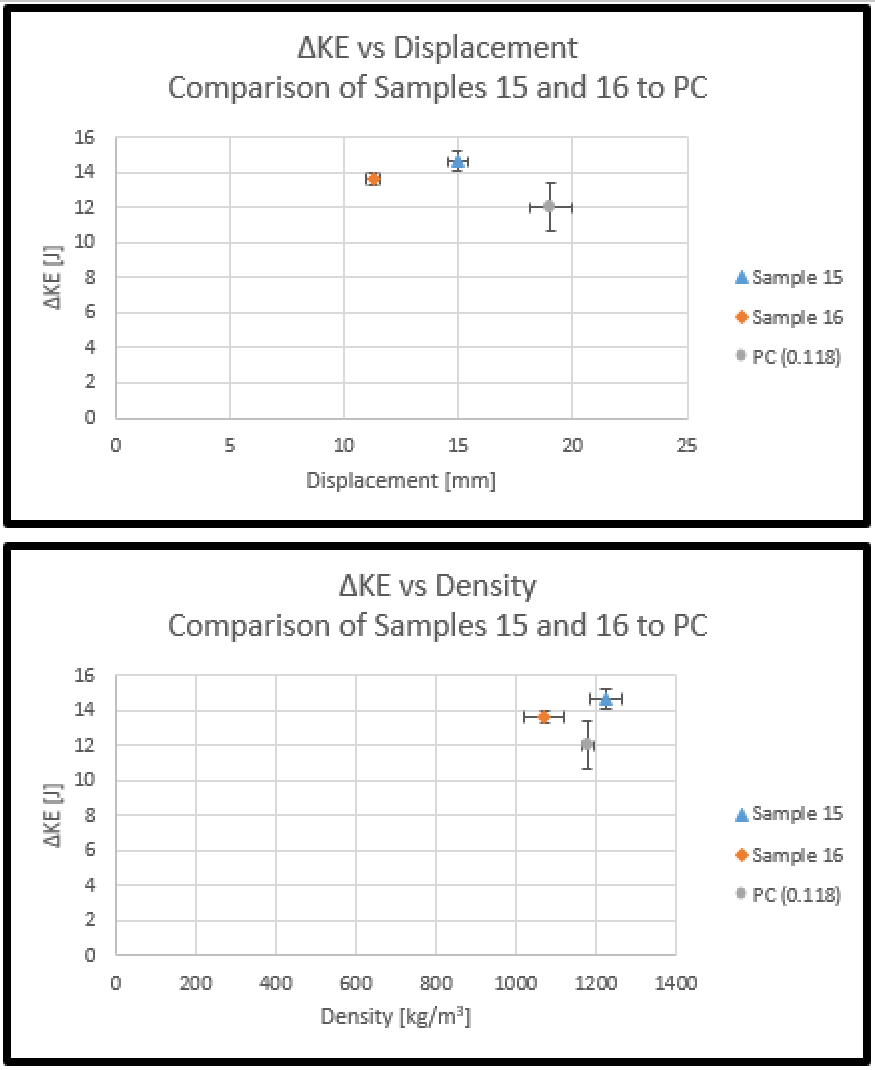
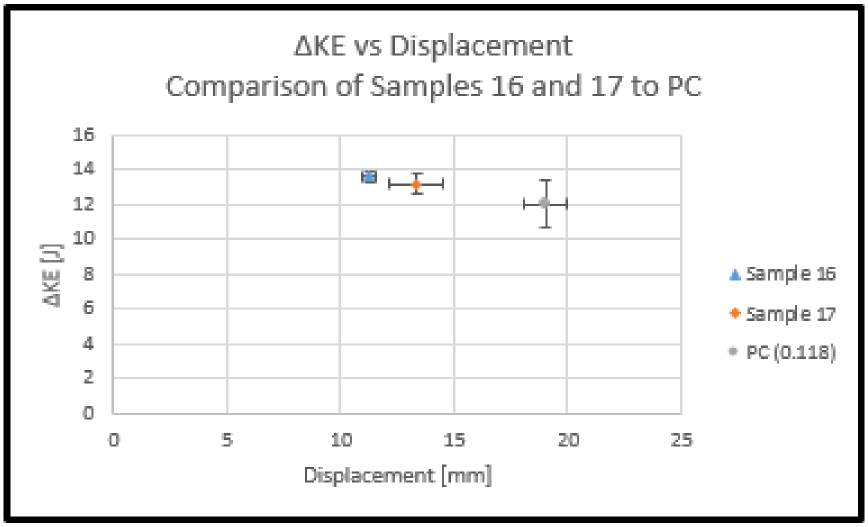


Figure C.7 Representation of the ΔKE related to displacement and density for composite samples 15 and 16.



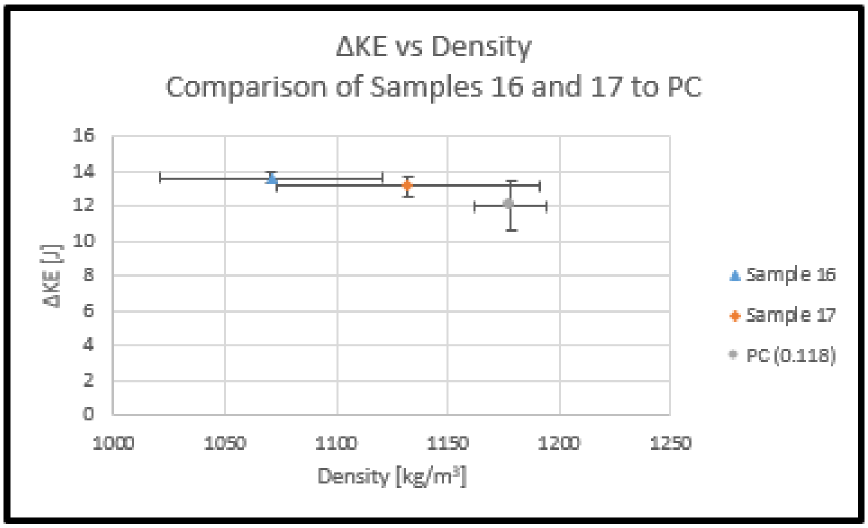


Figure C.8 Representation of the ΔKE related to displacement and density for composite samples 16 and 17.

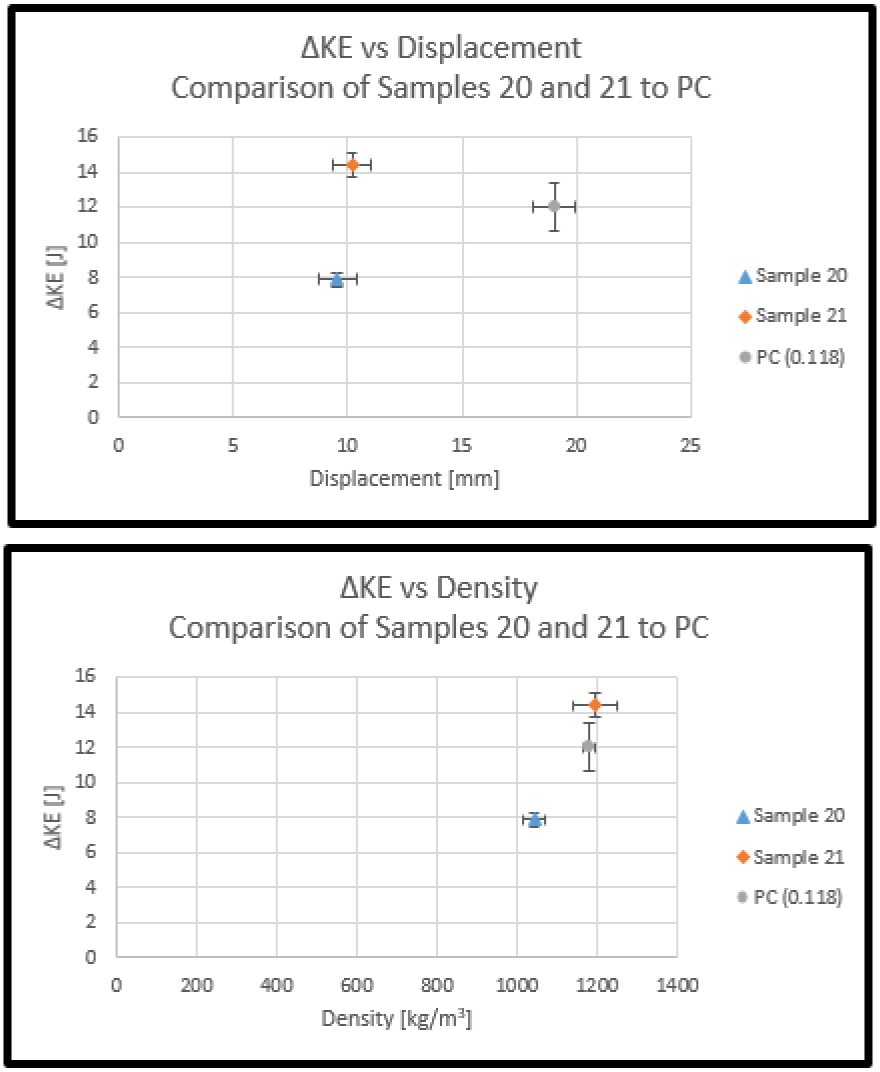
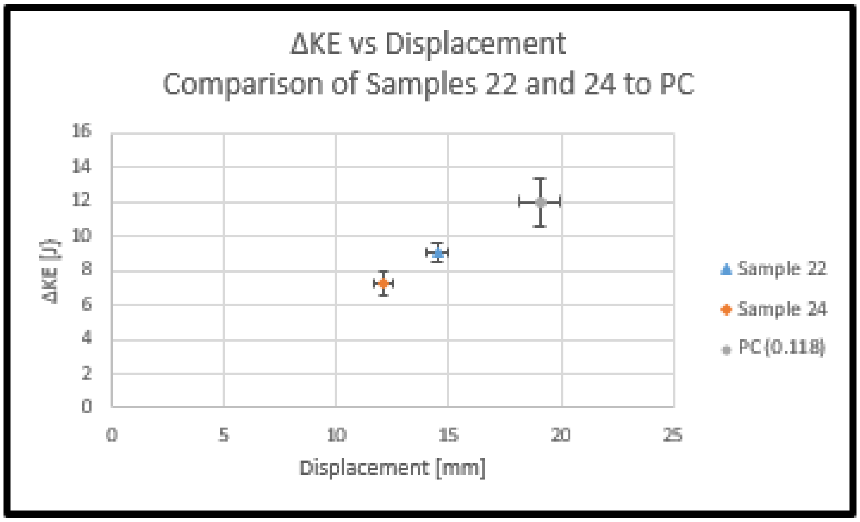


Figure C.9 Representation of the ΔKE related to displacement and density for composite samples 20 and 21.



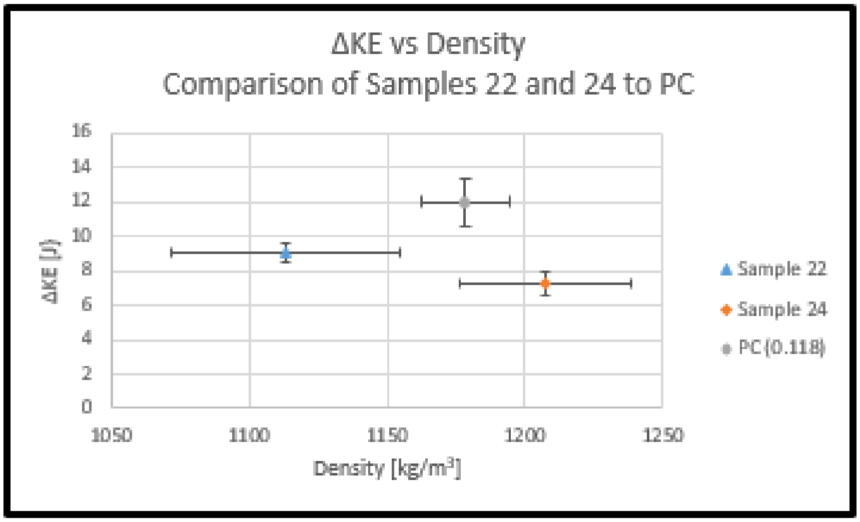


Figure C.10 Representation of the ΔKE related to displacement and density for composite samples 22 and 24.

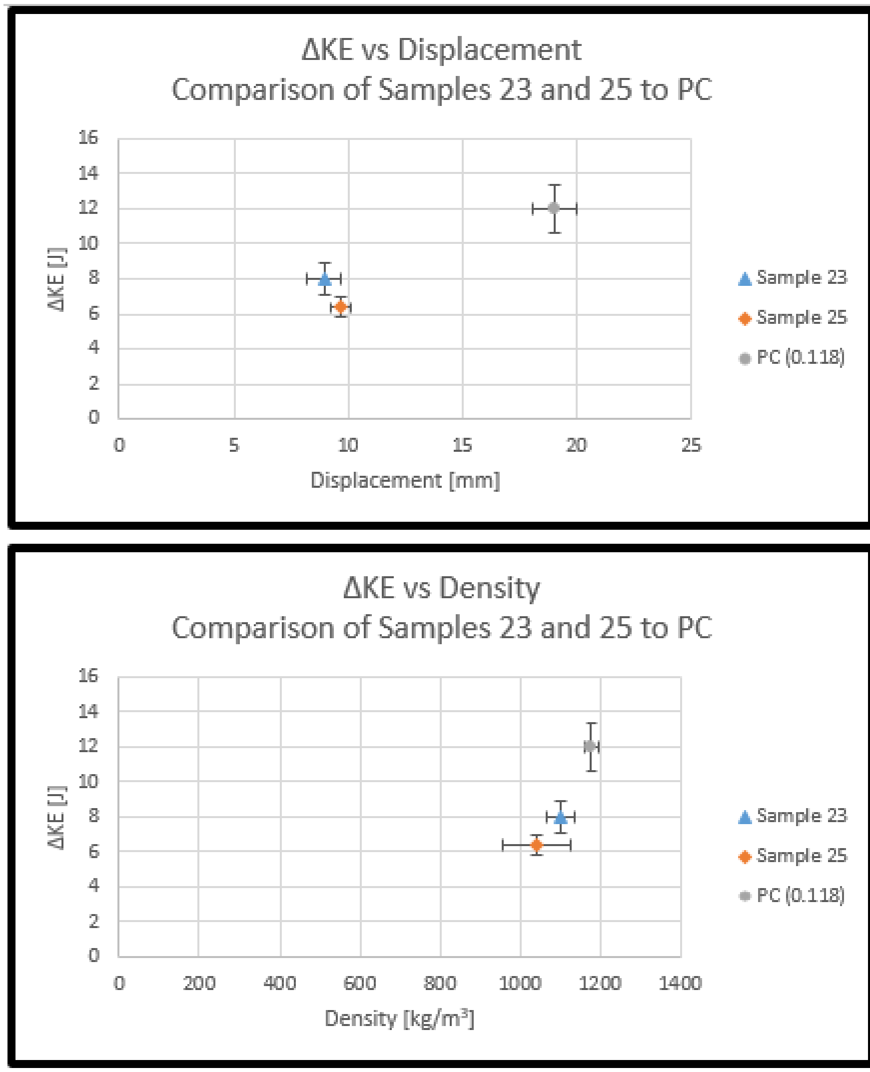


Figure C.11 Representation of the ΔKE related to displacement and density for composite samples 23 and 25.

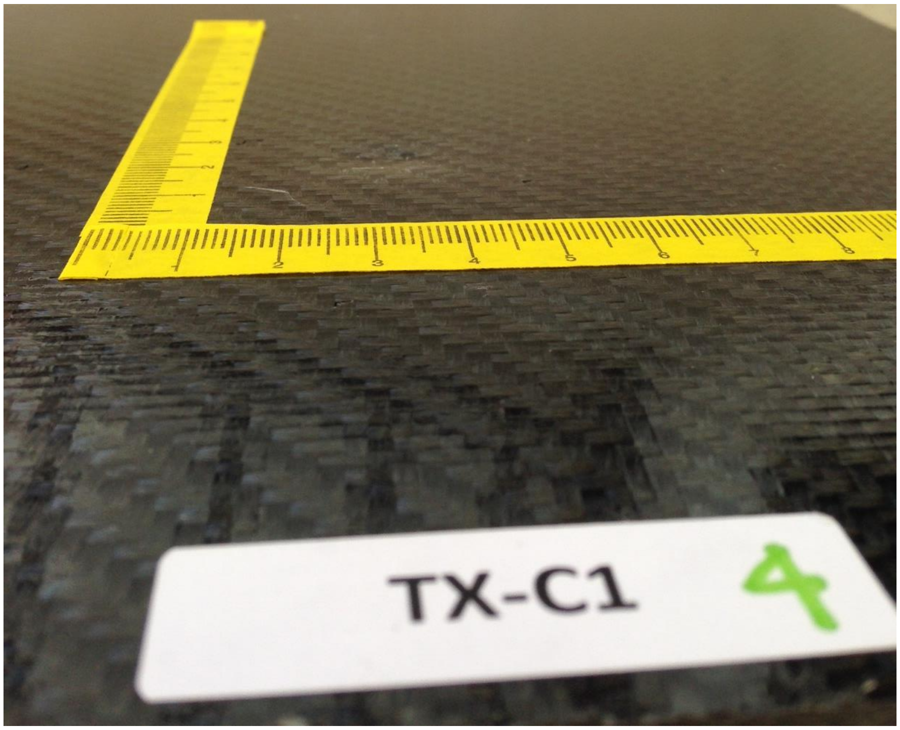


Figure C.12 Surface damage to Sample 1.

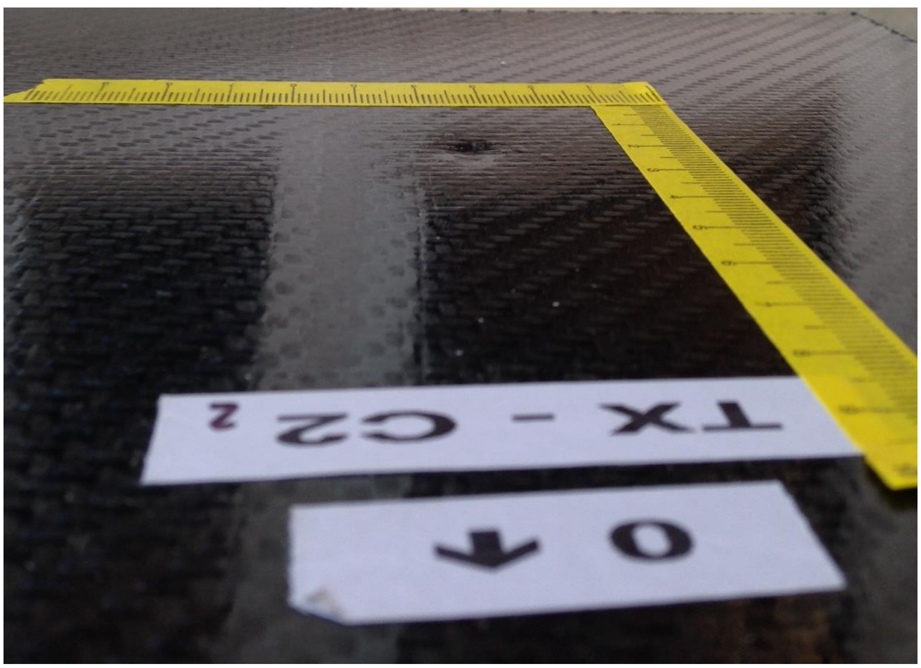


Figure C.13 Surface damage to Sample 2.

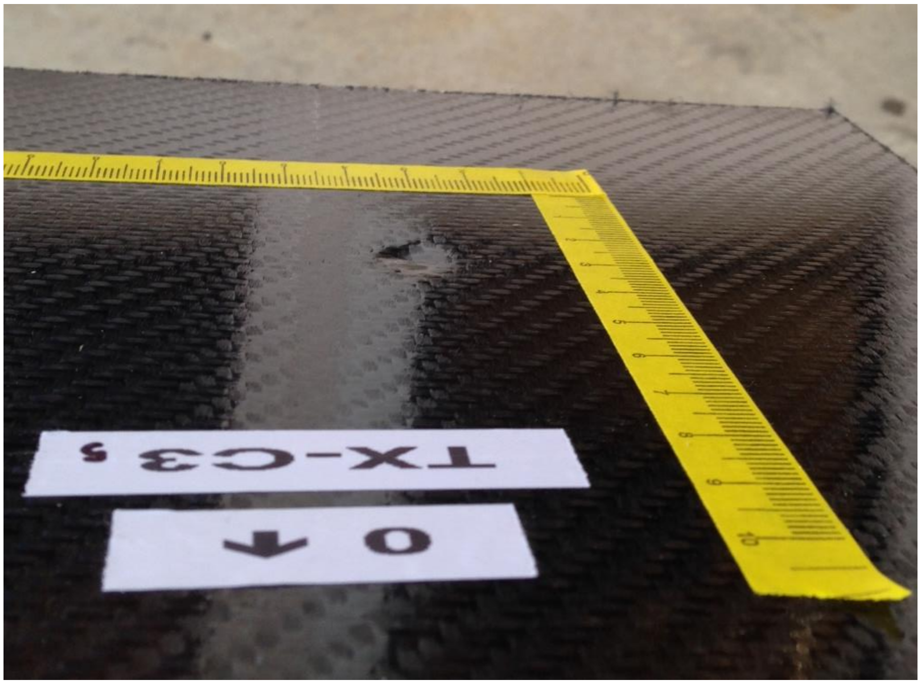


Figure C.14 Surface damage to Sample 3.

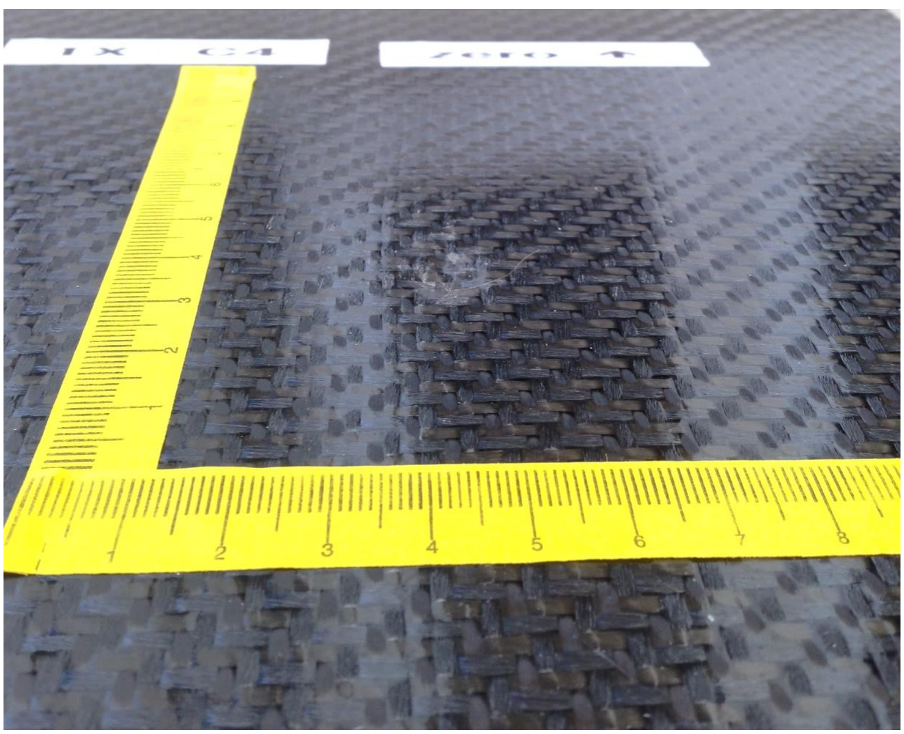


Figure C.15 Surface damage to Sample 4.

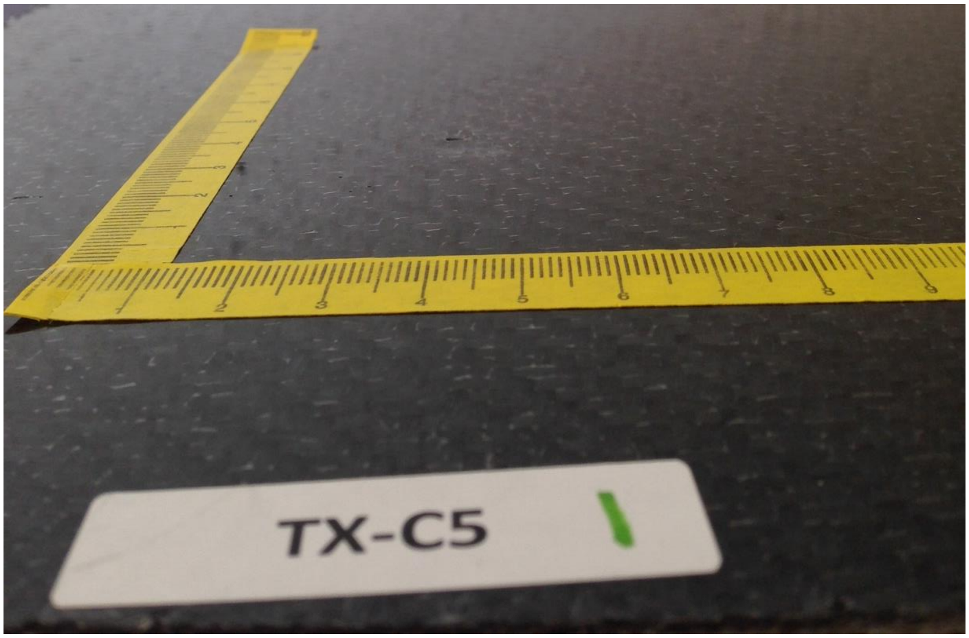


Figure C.16 Surface damage to Sample 5.

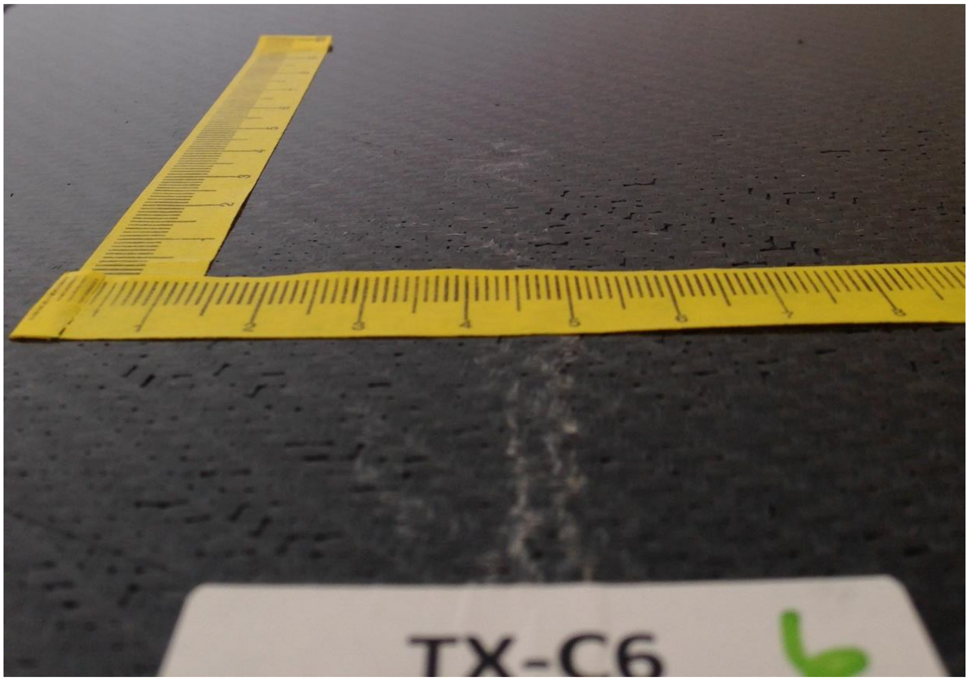


Figure C.17 Surface damage to Sample 6.

Figure C.18 Surface damage to Sample 7.

Figure C.19 Surface damage to Sample 8.

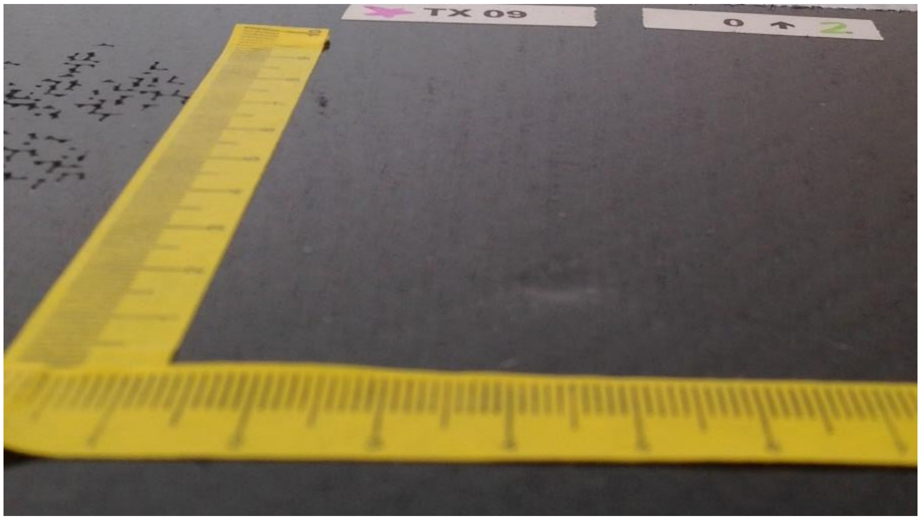


Figure C.20 Surface damage to Sample 9.

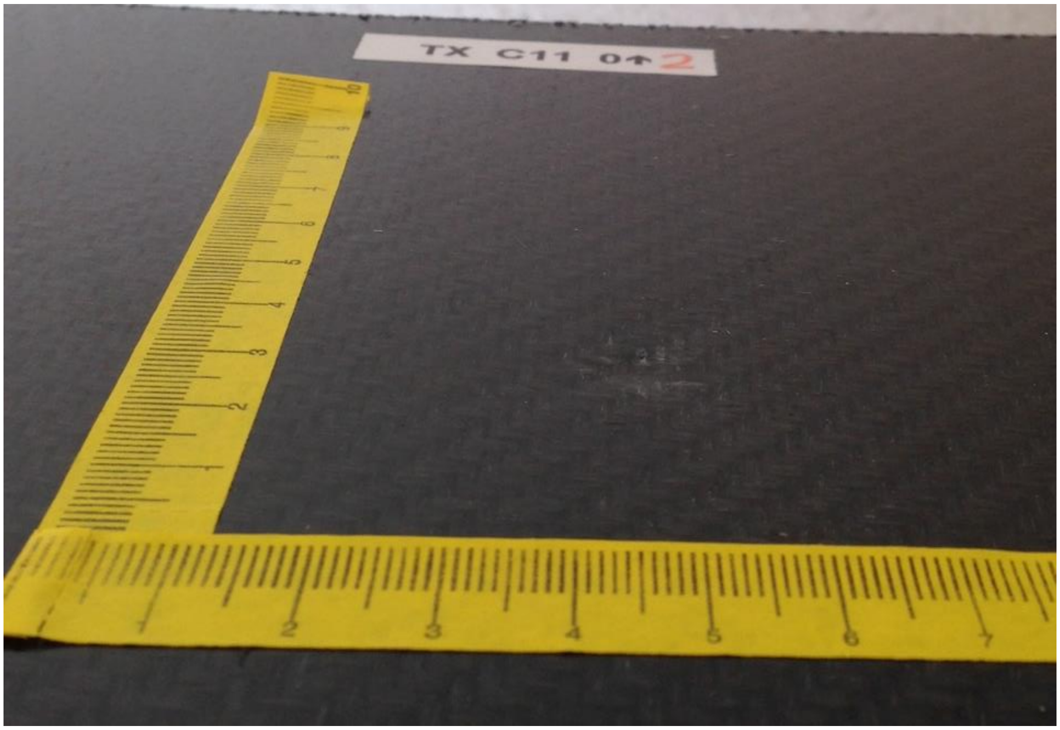


Figure C.21 Surface damage to Sample 11.

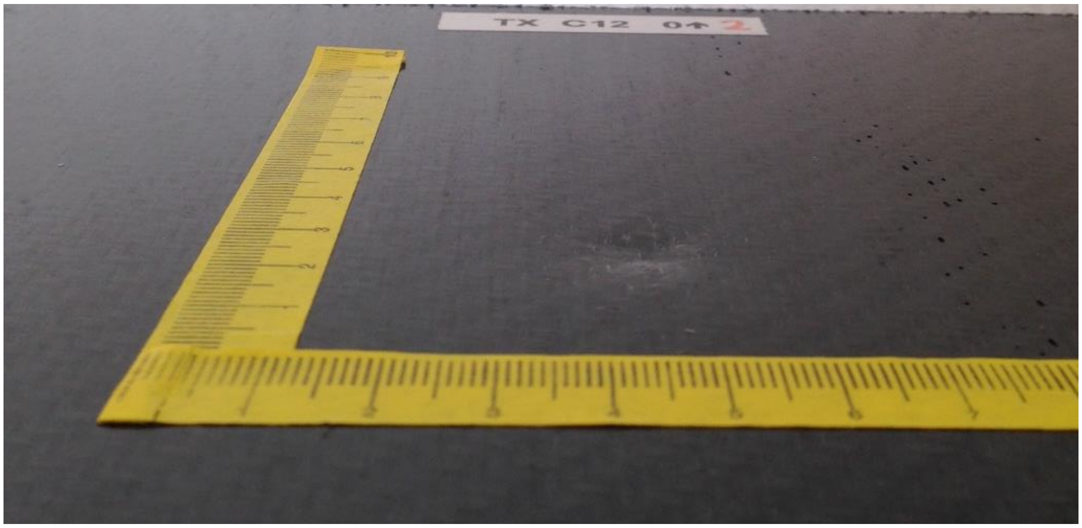


Figure C.22 Surface damage to Sample 12.

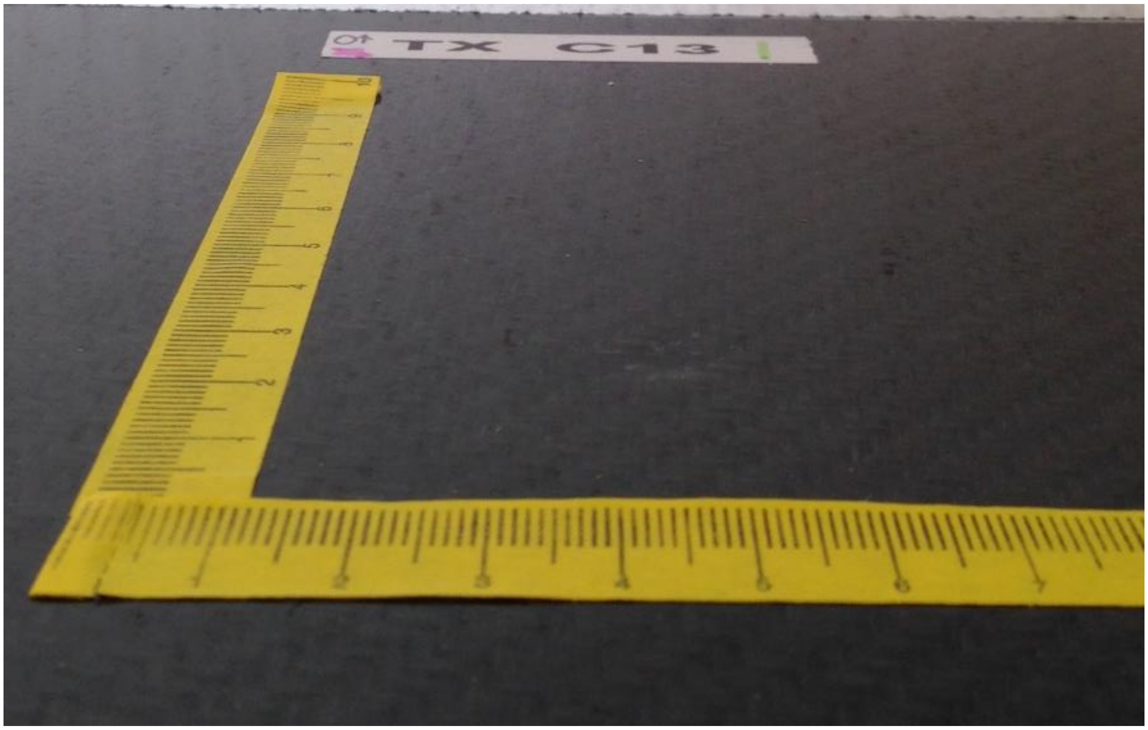


Figure C.23 Surface damage to Sample 13.

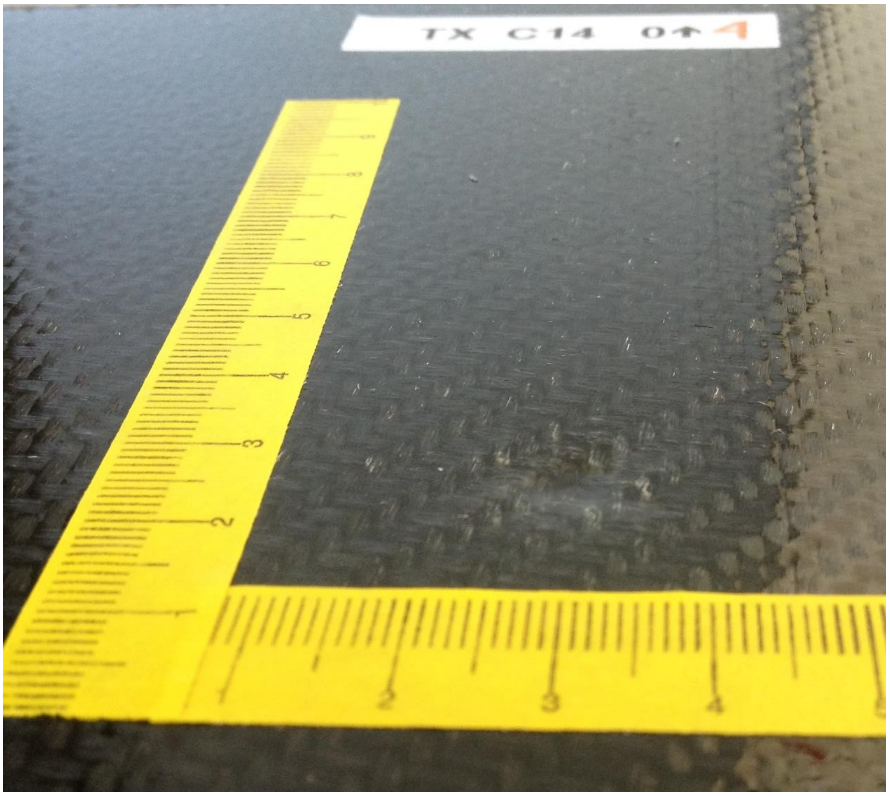


Figure C.24 Surface damage to Sample 14.

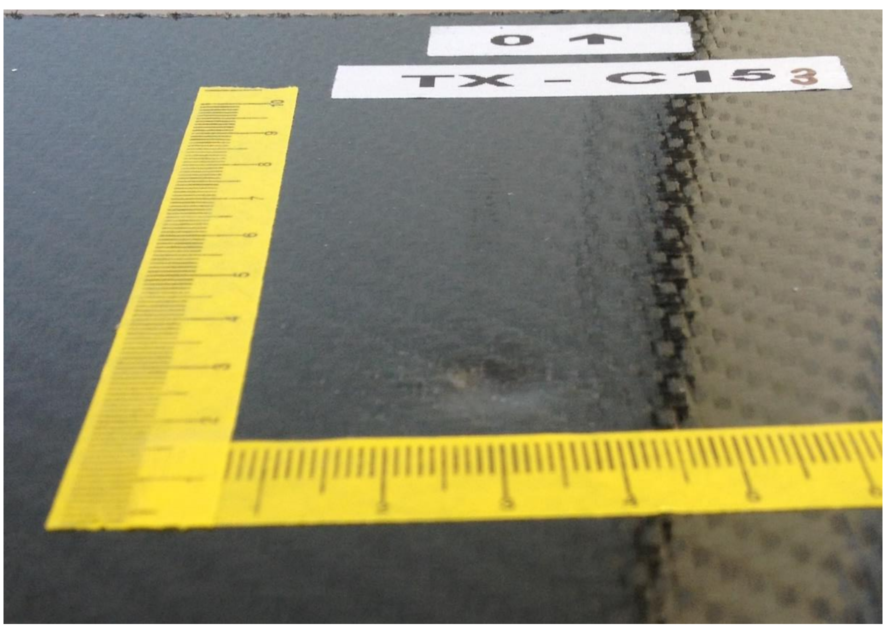


Figure C.25 Surface damage to Sample 15.

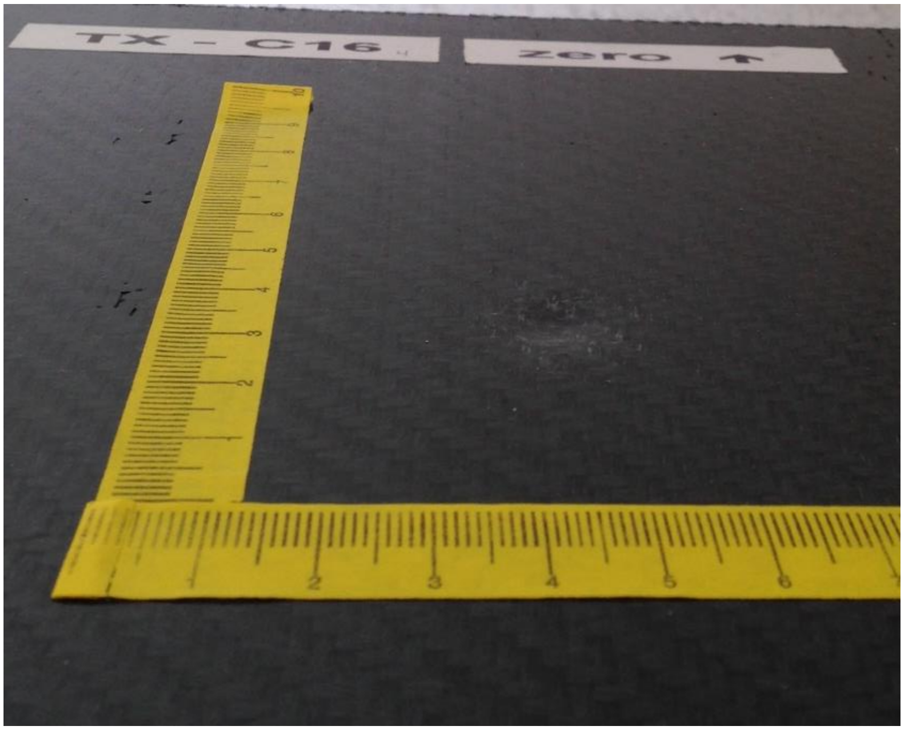


Figure C.26 Surface damage to Sample 16.

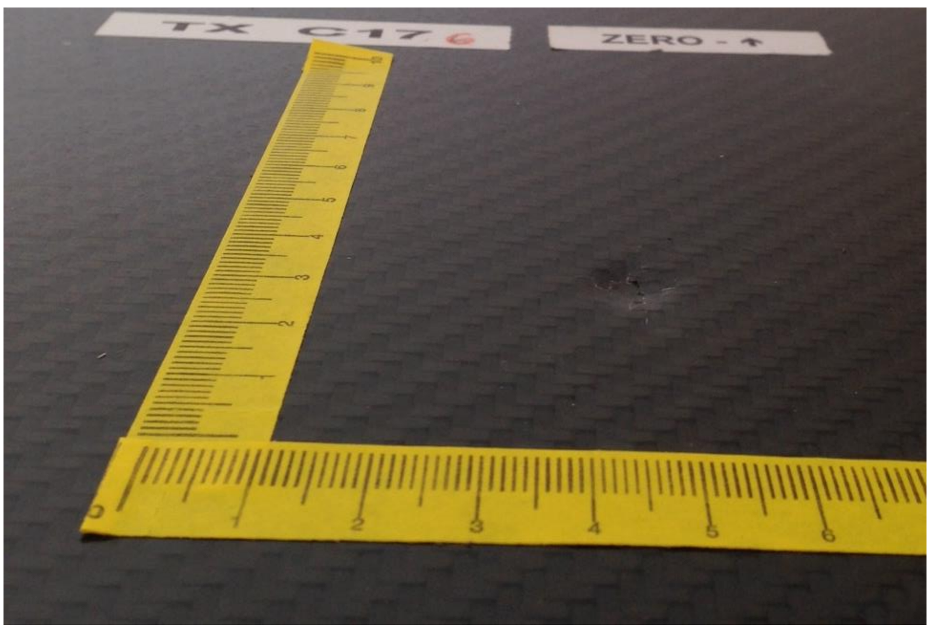


Figure C.27 Surface damage to Sample 17.

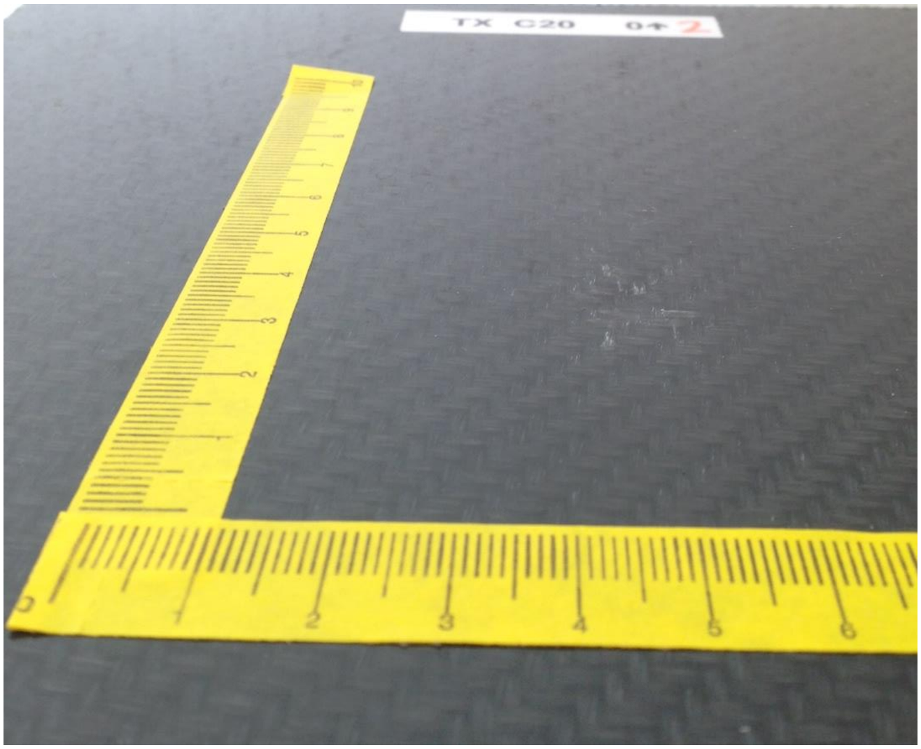


Figure C.28 Surface damage to Sample 20.

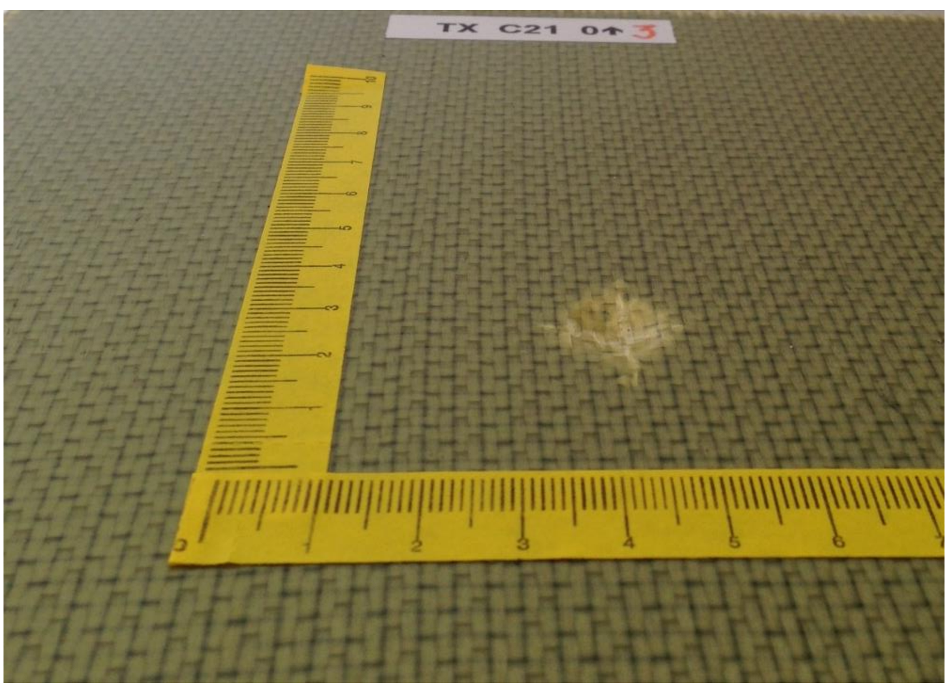


Figure C.29 Surface damage to Sample 21.

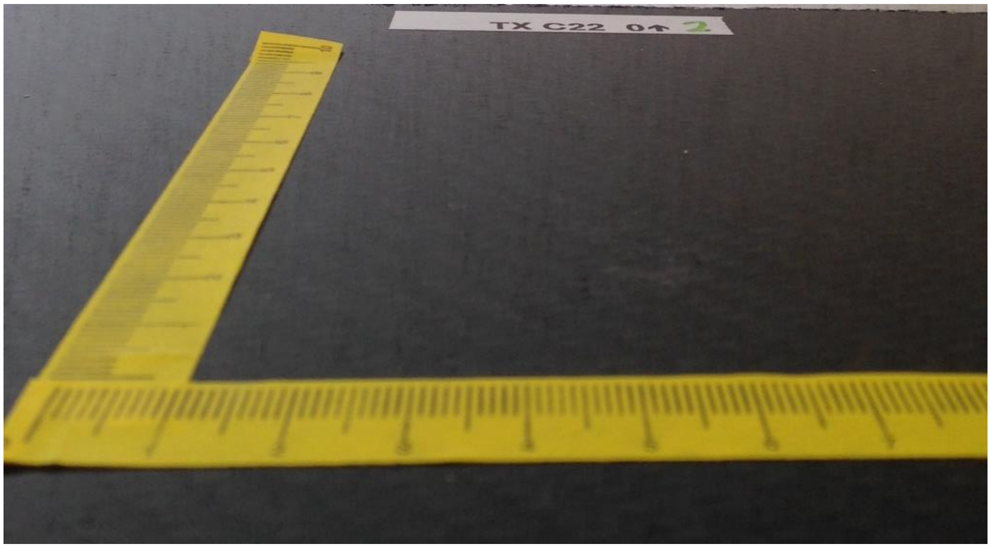


Figure C.30 Surface damage to Sample 22.

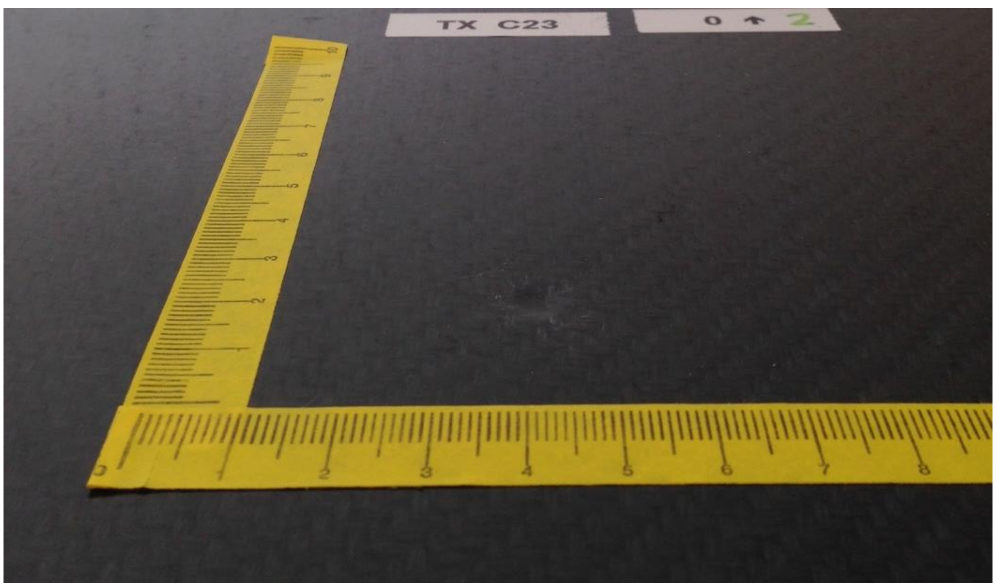


Figure C.31 Surface damage to Sample 23.

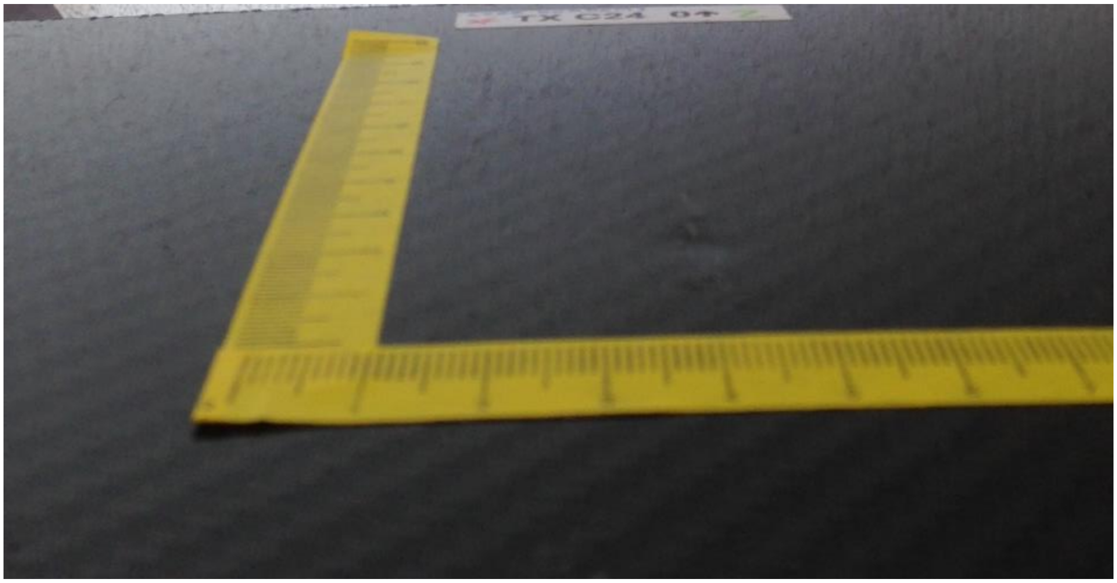


Figure C.32 Surface damage to Sample 24.

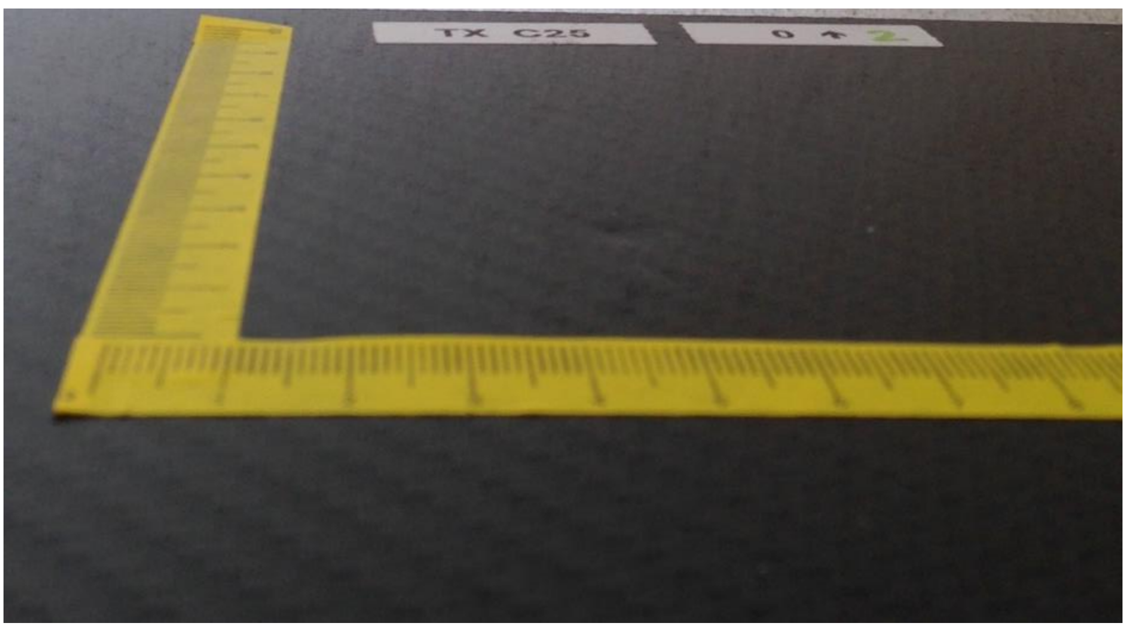


Figure C.33 Surface damage to Sample 25.

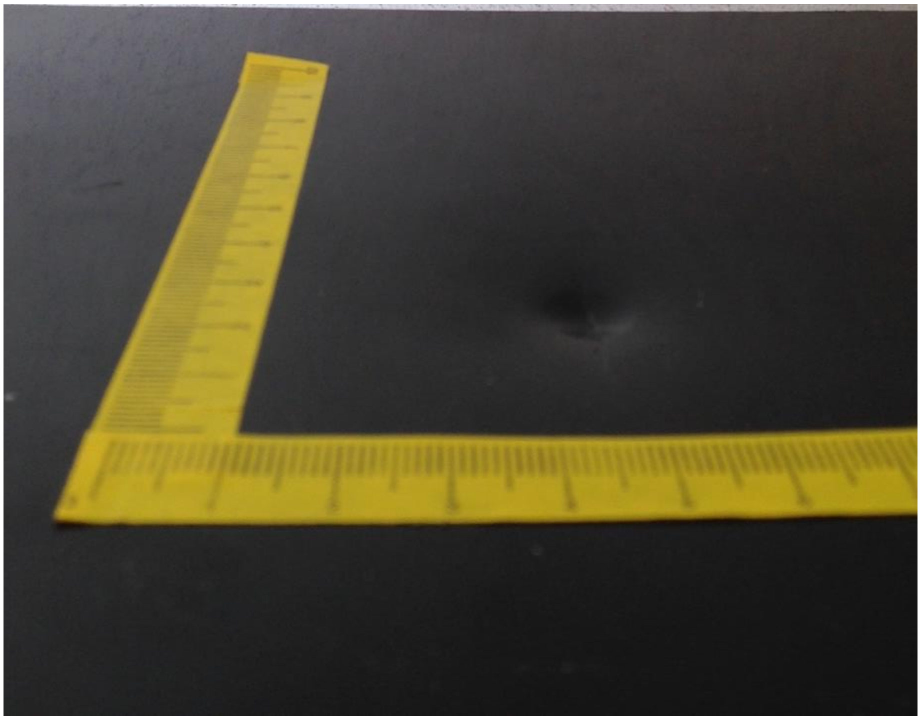


Figure C.34 Surface damage to ABS.

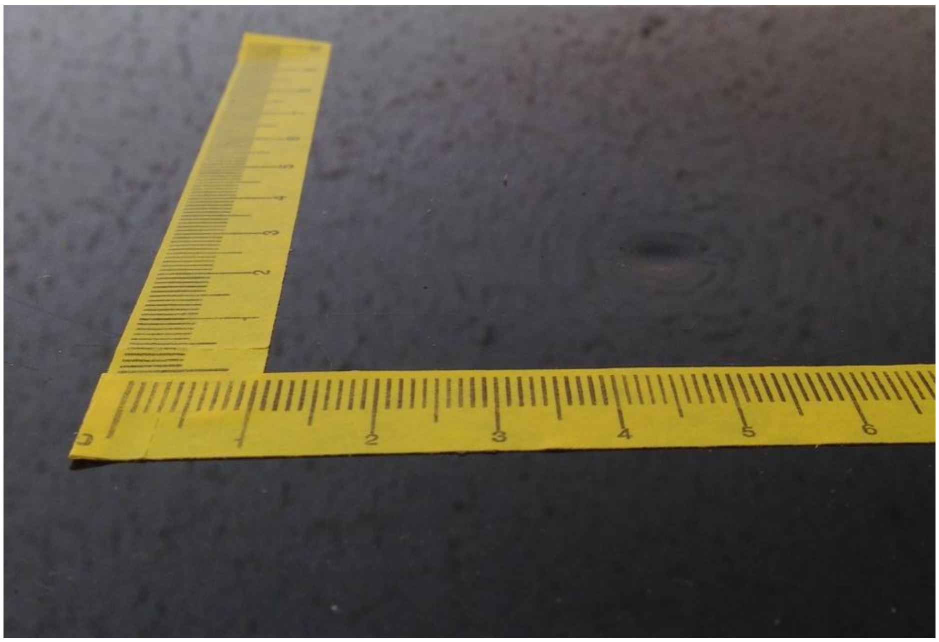


Figure C.35 Surface damage to PC.

APPENDIX D

Larger Impactor

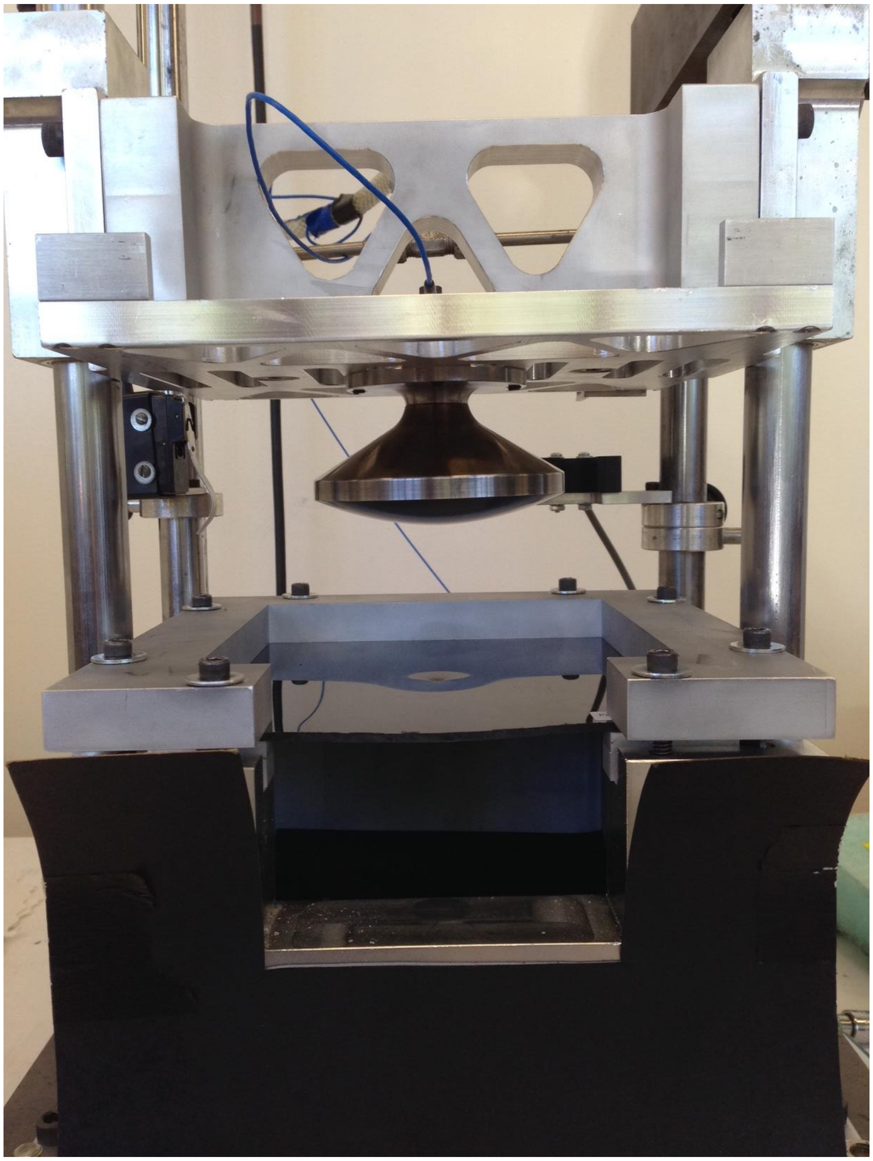


Figure D.1 Front view of the Cushion Tester equipped with the larger impactor that will be used for dynamic drop weight impact testing for Phase II.

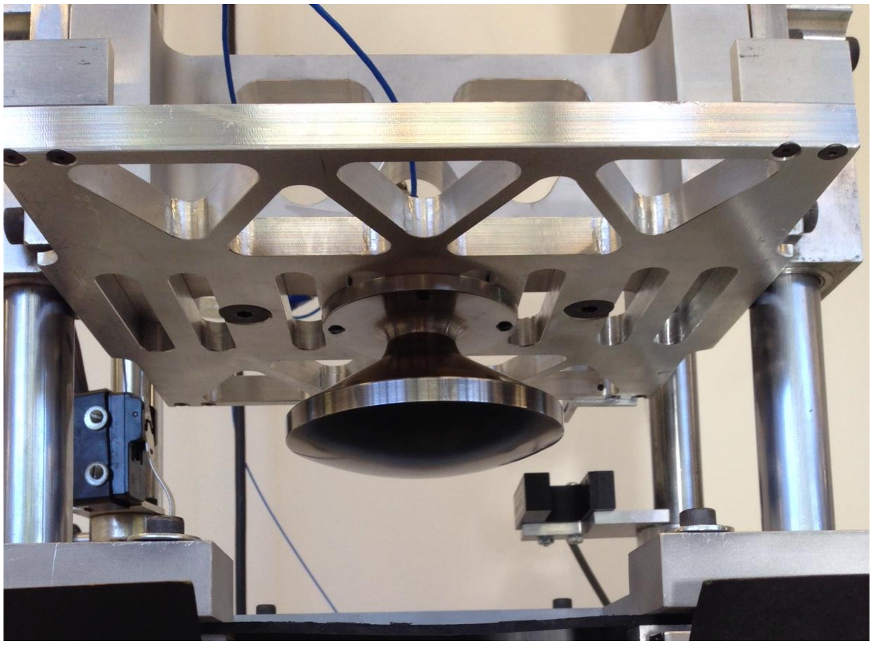


Figure D.2 Inferior view of the Cushion Tester equipped with the larger impactor that will be used for dynamic drop weight impact testing for Phase II.

CHAPTER THIRTEEN

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